Soil Genesis and Vegetation Response to Amendments and Microtopography in Two Virginia Coastal Plain Created Wetlands

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Abstract (Academic)

Wetlands serve important ecosystem functions such as carbon sequestration but are often affected by disturbances like urban development, agriculture, and road building. For wetlands created to mitigate losses, it is important that the ecosystem functions successfully replicate those of natural wetlands. Created wetlands have frequently not provided these functions due to issues including low organic carbon (OC), high soil bulk density (BD), lost topsoil, incorrect hydrology, and failure of targeted vegetation establishment. Organic matter (OM) amendments help created wetlands attain these functions quicker, but, their long-term effects are seldom reported. This research's purpose was to measure the long-term effects of treatments at a sandy tidal freshwater wetland created in 2003 (WWE) and a fine-textured, non-tidal wetland created in 2002 (CCW). We tested OM treatments, topsoil amendment, and microtopography effects on soil and vegetation properties at WWE and OM treatments at CCW. Pedogenic changes in soil morphology, physical and chemical properties were detected by comparing data to previous studies at these sites. At both sites, litter and biomass parameters were measured to estimate total mass C. Herbaceous biomass was measured at WWE. At WWE, no long-term OM treatment effects from 78 or 156 Mg ha^{-1} were observed. Soils in pits had higher OC, lower BD, and lower chroma than soils on mounds. Sandy and loamy HSFI's developed at WWE within four years, but there were fewer sandy indicators after 12 years. Loamy HSFI's were lost at CCW from 2003 to 2016. Plots at WWE that were amended with topsoil had higher soil mass C than the sandy soil due to a finer texture, but total mass C did not vary. At CCW, long-term OM treatment effects were observed, including lower BD, higher soil mass C, and higher tree mass C with increasing compost rates up to 224 Mg ha^{-1}. Overall, the ideal compost loading rate for constructed wetlands varied with wetland type and mitigation goals. Compost rates of 112 Mg ha^{-1} are sufficient for short term establishment of wetland vegetation and hydric soil properties, but higher rates near 224 Mg ha^{-1} may be required for effects that last over 10 years.

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Abstract (Public)

Wetlands are unique habitats that provide environmental benefits such as carbon storage but are often negatively affected by human disturbances such as urban development and road construction. When wetlands are constructed to mitigate natural wetland losses, it is important that they successfully provide the benefits of the wetlands they replace. Created wetlands have frequently not functioned like natural wetlands due to soil issues including low organic carbon (OC) and high soil density (BD). Organic matter (OM) amendments such as composted yard waste help created wetlands attain these functions quickly after construction compared to unamnded wetlands. The purpose of this study was to measure long-term (greater than 10 years) effects of OM treatments on soil and vegetation properties at two different created wetlands. The two wetlands were a sandy tidal freshwater wetland created in 2003 (WWE) and a fine-textured, compacted, non-tidal wetland created in 2002 (CCW). Previous soil data were compared to recent soil samples to detect changes in physical and chemical soil properties over time. At WWE, soils in pits accumulated more OM, were higher in carbon, lower in BD, and had greyer color than soils in mounds. Hydric soil field indicators developed from upland soil within four years after construction at WWE. There were no long term compost effects on soil properties compared to a fertilized control, but the compost rates used were low compared to other recommendations, and the wetland was constructed carefully to avoid compaction. There were much higher rates of compost applied at CCW, which produced lower BD, higher soil mass C, and higher tree biomass. We recommend applying OM and avoiding compaction during wetland construction. Ideal OM loading rate depends on wetland type (soil texture, hydrology) and mitigation goals. In the fine-textured, compacted wetland studied here, compost rates of 112 Mg ha^{-1} are ideal for short term establishment of wetland vegetation and soil properties, but higher rates near 224 Mg ha^{-1} may be required for long term effects.

Dedication

To Mr. Bean, my first shelled companion in life. Only my family and a couple close friends have been with me longer. You have been a fixture in my life for twenty years, may you be with me for twenty (or forty) more. I hope this research in mitigation wetlands helps at least indirectly the native turtle populations of the Eastern United States.

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I would still be out in a wetland collecting samples if it wasn't for the help and hard work of Dr. Galbraith, several graduate students, and many undergraduate students. Thank you to everyone who helped me cut down trees, mark plots, describe soils, and take samples. Many hours went into this work and I could not have done it on my own.

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Attributions

Below is a brief summary of the roles played by several people that contributed significantly to the completion of the research in and writing of this dissertation and the chapters to which they contributed.

Chapter 2: Effects of Amendments and Microtopography on Created Tidal Freshwater Wetland Soil Genesis and Morphology

Emily Ott: PhD candidate in the Department of Crop and Soil Environmental Sciences, Virginia Tech. Ms. Ott performed field research, digitized soil description data from 2005 and 2007, lab analysis (soil particle size), ran statistical analysis tests and prepared the manuscript represented in this chapter.

John Galbraith: Associate Professor in the Department of Crop and Soil Environmental Sciences, Virginia Tech. Dr. Galbraith assisted with field research (plot marking, tree cutting, soil sampling, soil descriptions), committee advising, and with manuscript writing/editing.

W. Lee Daniels: Professor in the Department of Crop and Soil Environmental Sciences, Virginia Tech. Dr. Daniels designed and installed the experiment analyzed here and provided site background information, including soil description data from 2005, 2007, and site construction photos, committee advising, and assisted with manuscript editing.

W. Michael Aust: Professor in the Department of Forest Resources and Environmental Conservation, Virginia Tech. Dr. Aust assisted with committee advising and manuscript editing.

James Perry: Professor at the Virginia Institute of Marine Science, College of William and Mary. Dr. Perry assisted with committee advising.

Chapter 3: Amendment and Microtopography Effects on Bulk Density and Chemical Properties in Created Tidal Sandy Freshwater Wetland Soils

Emily Ott: Ms. Ott collected samples and performed lab analysis (e.g. BD determination, TC and TN), ran statistical analysis tests and prepared the manuscript represented in this chapter.

John Galbraith: Dr. Galbraith assisted in field work (sample collection) and with manuscript editing.

W. Lee Daniels: Dr. Daniels designed and installed the experiment analyzed here and provided previous site data and assisted with manuscript editing.

W. Michael Aust: Dr. Aust assisted with manuscript editing.

Chapter 4: Effects of Compost Amendments on Virginia Created Wetland Soils 14 Years After Application

Emily Ott: PhD candidate in the Department of Crop and Soil Environmental Sciences, Virginia Tech. Ms. Ott performed field research (soil descriptions and sample collection), lab analysis (BD, soil particle size, TC and TN, extracts for nutrient availability), statistical analysis tests and prepared the manuscript represented in this chapter.

John Galbraith: Dr. Galbraith assisted in field work (soil descriptions, sample collection) and with manuscript editing.

W. Lee Daniels: Dr. Daniels designed and installed the experiment analyzed here and provided previous site data and assisted with manuscript editing.

W. Michael Aust: Dr. Aust assisted with manuscript editing.

James Perry: Dr. Perry assisted Dr. Daniels in the design of the experiment.

Chapter 5: Soil Organic Matter and Topsoil effects on Mass Soil Carbon in Two Created Wetlands

Emily Ott: PhD candidate in the Department of Crop and Soil Environmental Sciences, Virginia Tech. Ms. Ott performed field work (collection of root, litter, and herbaceous biomass samples, tree measurements), lab work (separation of herbaceous biomass), statistical analyses, and prepared the manuscript represented in this chapter.

John Galbraith: Dr. Galbraith assisted in field work (root sample collection, tree measurements) and with manuscript editing.

W. Lee Daniels: Dr. Daniels designed both experiments and assisted with manuscript editing.

W. Michael Aust: Dr. Aust provided tools (e.g. height pole, root auger) and assisted with manuscript editing.

Dr. James Perry assisted with the design of the experiment at Charles City Wetland and with the overall vegetation assessment protocols utilized at both sites.

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1. Introduction

Wetlands Background

Importance

The United States drained, ditched, and filled many wetlands starting in the 1700s (Dahl, 1990). Some government agencies encouraged this behavior as it allowed for agricultural and urban development (Mitsch and Gosselink, 2007). More recently, organizations including scientists, engineers, lawyers, and regulators are finding it useful and necessary to understand, preserve, and reconstruct wetland ecosystems to maintain or restore their intrinsic functions and values.

Wetland ecosystems are defined by three essential interlinked components: the presence of water at the surface or in the root zone (flooding or saturation); hydric soil conditions unique and different from upland soils; and vegetation adapted to wet conditions. Wetlands provide ecological functions such as sediment trapping, floodwater retention, groundwater recharge, water purification, nutrient sequestration and/or removal, and unique habitats for endangered species. This has caused wetlands to be considered "the kidneys of the landscape" (Mitsch and Gosselink, 2007). Wetland ecosystems are among the most productive in the world, but not all wetlands perform the same functions or perform functions equally well. Isolated wetlands, for example, provide ecosystem functions such as habit for waterfowl feeding and nesting, habitat for upland and wetland wildlife species, local runoff detention and infiltration, sediment and nutrient retention, and aesthetic qualities. Riverine wetlands provide similar functions, in addition to being floodwater storage and conveyance areas, providing sediment control, and stabilization of river banks (Novitski et al., 1996).

Another important wetland function is carbon (C)-sequestration via soil OM and living biomass accumulation. Wetlands are also responsible for emitting methane, nitrous oxide, and other greenhouse gasses. Some estimate that wetlands emit 115–227 Tg-methane (CH_4) year^{-1}, which is 20–25% of current global methane emissions (Whalen 2005; Bergamaschi et al. 2007; Bloom et al. 2010). Mitsch et al. (2012) showed that the methane emissions from temperate and tropical wetlands became unimportant when compared to C sequestration over 300 years. Seven temperate and tropical wetlands were studied, and a model was constructed to simulate the net atmospheric radiative forcing (due to both CO_2 and methane fluxes) and C exchange of these wetlands. The model was then used on 14 more wetlands, including temperate, tropical, and boreal wetlands, to evaluate the net radiative forcing and C exchange. These wetlands and model were used to estimate net differences in C retention by wetlands on a global scale. The authors estimated that the world's wetlands may be net C sinks of 830 Tg $year^{-1}$ of C with a weighted average of 118 g-C m−2 $year^{-1}$ of net C retention (Mitsch et al., 2012).

The majority of the 118 g-C m^{-2} $year^{-1}$ of net C retention occurs in tropical and subtropical wetlands, due to their global extent. The total amount of the world's tropical and sub-tropical wetlands is approximately 2.9 x 106 km^2, while the area of temperate wetlands is 0.6 9 x 106 km^2 (Lehner and Döll, 2004; Mitsch and Gosselink, 2007). When balancing methane emissions and C sequestration, almost all wetlands are net sinks with respect to greenhouse gasses released into the atmosphere. The authors found "that wetlands can be created and restored to provide C sequestration and other ecosystem services without great concern of creating net radiative sources on the climate due to methane emissions" (Mitsch et al., 2012). This, in addition to the ecosystem service that wetlands provide, led the authors to conclude that it is "shortsighted" to suggest wetland creation and restoration efforts should be limited due to concerns over greenhouse gas emissions (Mitsch et al., 2012).

Regulation

The Clean Water Act (CWA; Public Law 92-500, 33 U.S.C 1251) was passed in 1972 to prevent pollution of the Nation's waters, and maintain their "chemical, physical, and biological integrity". Section 404 of the CWA established regulation of the discharge of dredge and fill material into waters of the U.S.

and gave regulation authority to the U.S. Army Corps of Engineers (COE). "Waters of the U.S." includes traditional navigable waters, interstate waters, wetlands adjacent to either traditional navigable waters or interstate waters, non-navigable tributaries, and wetlands that are directly adjacent to relatively permanent waters. Other wetlands, such as those adjacent to jurisdictional tributaries of traditional navigable waters, can be considered jurisdictional if they have "significant nexus" to traditional navigable water (EPA, 2012). The ruling of the 2006 Supreme Court case, Rapanos vs. United States, removed federal jurisdiction for isolated wetlands where a "significant nexus" does not exist. A wetland with significant nexus has a significant effect on the chemical, physical, or biological properties of traditional navigable waters (downstream waters of the U.S.). A case-specific analysis must be performed to test whether an unnavigable wetland is protected (EPA, 2012; Cabrera, 2015).

A CWA Section 404 permit must be obtained from the COE to dredge or fill waters of the U.S. Jurisdictional wetlands are included in waters of the U.S., and there are criteria that a wetland must meet in order to be protected under Section 404 of the Clean Water Act (COE, 2010). Agricultural wetlands that were not farmed or pastured before 1985 are regulated by the Food Security Act of 1985 (Public Law 99–198, Title XII), and fall under the jurisdiction of the National Resources Conservation Service (NRCS) (NRCS-SCS, 1985). Most states also regulate wetland impacts in concert with and often in addition to COE requirements. For example, the VA Department of Environmental Quality (DEQ) regulates impacts to isolated wetlands in addition to those with significant nexus to waters of the USA.

In Virginia, the COE and the DEQ evaluate constructed wetlands to determine whether they meet permit release conditions. The same four characteristics are used to determine created wetland jurisdiction, which are: saturated or inundated hydrology for at least 5% of the growing season (or longer depending on district); hydric soil determined by a hydric soil field indicator (HSFI) or the hydric soil technical standard (HSTS) for problem soils; and hydrophytic vegetation using the Rapid Test for Hydrophytic Vegetation, a Dominance Test, or a Prevalence Index (COE, 2010).

Losses and Creation

During colonial times in America, and up until the late 1900's, wetlands were regarded as wastelands that should be drained, filled, or otherwise manipulated to use for agriculture, forestry, urban development or other human land uses. From pre-settlement to the mid-1980's, over half (53%) of the wetlands in the contiguous U.S. were lost (Dahl, 1990). During this time, Virginia lost approximately 42% of its wetlands (Dahl, 1990). Roughly one third of all wetlands lost in the country were in the farm belt states (Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin). The loss of wetlands in this country has seriously impacted their provision of environmental and socio-economic benefits, such as groundwater supply, water quality, shoreline erosion, floodwater storage, trapping of sediments, and climatic changes (Dahl, 1990).

In 1988, the National Wetlands Policy Forum, part of the Environmental Protection Agency, recommended that:

> "the nation establish a national wetlands protection policy to achieve no overall net loss of the nation's remaining wetlands base, as defined by acreage and function, and to restore and create wetlands, where feasible, to increase the quality and quantity of the nation's wetland resource base" (Kean et al., 1988).

President George Bush Sr. repeated this 'no net loss' policy as a national goal in 1989, which resulted in protection of wetlands under section 404 of the Clean Water Act (Public Law 92-500, 33 U.S.C 1251). The COE is in charge of granting permits to allow disturbance or destruction of a wetland, and if a permit is granted, then impact mitigation must take place.

In general, the appropriate sequence of wetland impact mitigation (governed by the COE and individual state policies) is considered to be avoidance of impacts, minimization of actual on-site impacts, restoration of impacts on-site or nearby and then finally, off-site creation. Thus, off-site compensation is the last choice for mitigation after the other options have been exhausted. Off-site compensation can be wetland restoration or creation. For example, as of 1999, the Virginia Department of Transportation (VDOT) has created over 105 non-tidal mitigation wetlands (Whittecar and Daniels, 1999) because of road construction activities that filled or degraded wetlands.

An example of wetland restoration is to fill in ditches in previously converted farmland and reconnect the area to waters of the USA. Alternatively, new wetlands can be created when uplands are excavated to bring their surface closer to the water table, or when wetlands are hydraulically connected to a nearby source of surface water (Brinson and Rheinhardt, 1996). Creation of wetlands from uplands is the most difficult type of wetland mitigation to successfully accomplish (Zedler and Callaway, 1999). As described later, much research has been conducted on wetland creation and differential outcomes, but additional research is needed to develop appropriate site and soil reconstruction recommendations (e.g., organic matter (OM) amendments, topsoil amendments, and installation of microtopography).

Wetland Hydrology

According to Mitsch and Gosselink (2007), "hydrology is probably the single most important determinant of the establishment and maintenance of specific types of wetlands and wetland processes". Hydrology includes water depth, flow patterns, and duration and frequency of flooding, which influence soil biogeochemistry and wetland organisms. Wetland organisms (e.g. microbes, vegetation, and waterfowl) are limited or enhanced by wetland hydrology. Energy and nutrients are transported to and from wetlands through hydrologic pathways such as precipitation, surface runoff, groundwater, tides, and flooding.

One way to describe wetland hydrology is to measure the "hydroperiod". The hydroperiod is typically represented as a graph of a wetland's seasonal level of ponding or soil saturation and characterizes differing types of wetlands. The three factors that influence hydroperiod are: (1) the balance between water inflows and outflows; (2) landscape topography; and (3) subsurface soil, geologic, and groundwater conditions. Many early wetland case studies dealt with relationships between hydrologic variables such as water depth and wetland productivity or species composition (Mitsch and Gosselink, 2007). There are fewer studies that describe hydrologic characteristics in detail within specific wetland types (e.g. emergent vs. forested). The two types of forested wetland hydrology emphasized in this study are freshwater tidal and seasonally saturated wetlands.

Tidal wetlands have three types of water input: precipitation, groundwater, and surface water, but inputs and movement are dominated by surface water (Rabenhorst, 2001). The tidal flux in freshwater tidal wetlands may act as a stress by causing periodic submergence, forcing anaerobic soil conditions. However, tides also remove excess salts, periodically reestablish aerobic soil conditions, and provide nutrients. Rising coastal high tides typically carry salt water up a river or stream channel into estuaries and tidal wetlands. There is a natural salinity gradient from mouth (saline coastal water) to headwaters (freshwater wetlands), with brackish water in-between. Tidal action is not the same every day of the year. There are seasonal, monthly, and diurnal patterns in tides due to the gravitational pull of the moon and sun (Mitsch and Gosselink, 2007). Coastal wetlands are economically important ecosystems as they protect coastal regions from storms, sequester C, and support the commercial fishing industry (Barbier et al., 2011). These wetlands have historically been converted to upland for agricultural use or lost to aquaculture use and are susceptible to sea level rise (Barbier et al., 2011; Pendleton et al., 2012; Kirwan and Megonigal, 2013).

An understanding of wetland hydrology is important for delineation purposes. When delineating wetlands, hydrology indicators are used (along with hydric soil indicators and wetland vegetation indicators). Examples of primary wetland hydrology indicators include high water table and near surface ponding or saturation for the prescribed length, water marks, sediment deposits, hydrogen sulfide odor, and water-stained leaves. A site meets jurisdictional determination requirements for wetland hydrology if a primary indicator is present. If a primary indicator is not present, then two or more secondary indicators must be present, such as drainage patterns, moss trim lines, crayfish burrows, or saturation visible on aerial imagery. The absence of a hydrology indicator does not necessarily mean the absence of wetland hydrology. For example, some wetlands lack a hydrology indicator due to temporarily dry conditions or human disturbance (U.S. Army Corps of Engineers, 2010).

Growing season length and dates may be needed to evaluate hydrology indicators (i.e. visual observation of flooding or ponding), or to analyze recorded hydrologic data (i.e. stream gauge or water-table monitoring data), when determining whether an area is a jurisdictional wetland under COE governance.

Cowardin et al. (1979) defined the growing season as the frost-free part of the year, to determine hydrologic regimes in non-tidal wetlands. The period between the first and last killing frost was described as the dormant season (Cowardin et al., 1979). Regional supplements by the COE list specific criteria for determining the beginning and ends of the growing season in a given year. In the Atlantic and Gulf Coast region, the growing season has begun when either one of two conditions occurs first: 1) “two or more different non-evergreen vascular plant species growing in the wetland or surrounding areas exhibit one or more … indicators of biological activity” (COE, 2010), such as emergence from the ground, new growth from crowns, or budding on woody plants; 2) when soil temperature at 30 cm depth is 5 °C or higher. Long-term temperature should be monitored if hydrologic monitoring is planned to confirm that soil temperature remains 5 °C or higher during monitoring. The end of the growing season is determined “whichever condition persists later” (COE, 2010). Determining the hydrologic regime in seasonally saturated wetlands can take several years of data collection to accurately determine their hydroperiod (Karathanasis et al., 2003).

Wetland Soils

One of the first definitions of wetlands to introduce the term "hydric soil" was presented by Cowardin et al. (1979), a group of biologists, and adopted by the U.S. Fish and Wildlife Service:

> "Wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly undrained hydric soil; and (3) the substrate is nonsoil and is saturated with water or covered by shallow water at some time during the growing season of each year".

Other definitions of hydric soils exist, and the definitions have changed over time. The current NRCS definition of hydric soils are soils "that formed under conditions of saturation, flooding or ponding long enough during the growing season to develop anaerobic conditions in the upper part" (NRCS 2016). Hydric soils include soils that have altered hydrology (e.g. a drained field), if the soil in the unaltered state was hydric. Soils that are wet enough during the growing season due to artificial measures are also included in the concept of hydric soils. In soil classification, certain soil series are designated as hydric. These series may have phases that are not hydric, depending on flooding, and depth to the water table. Hydric soils are identified in the field by HSFI's, which use certain soil morphological characteristics that are only associated with wetland soils. These HSFI were "designed to identify soils which meet the hydric soil definition without further data collection" (NRCS 2016).

Hydric soil field indicators are based on morphological properties of wetland soils. Specifically, the accumulation or loss of iron (Fe), manganese (Mn), sulfur (S), or C compounds are the predominant factors of HSFI formation. Organic matter accumulation is another important factor in development of HSFI's. This is because soil microbes utilize organic-C at a lower rate in anaerobic environments than in aerobic environments, so partially decomposed OM tends to accumulate in wetland soils vs. adjacent uplands. The HSFI's are separated into three categories: All Soils - A; Sandy Soils - S; and Loamy and Clayey Soils - F (USDA-NRCS, 2010).

However, some soils form under hydric soil conditions but do not show hydric soil morphology; these are called problem hydric soils and atypical hydric soils. Wetland soils that may not meet a HSFI include recently developed wetlands, soils with shallow spodic materials, anomalous sandy soils, and soils with red parent materials. The HSTS may be used to test problem hydric soils. The HSTS should be used on soils that appear to meet criteria for wetland hydrology, connectivity, and hydrophytic vegetation, but fail to meet any field indicators of hydric soils. The tests under the HSTS involve determining that the area is likely to collect or concentrate water (such a depression, floodplain, or toeslope), and using a dye indicator such as α, α-dipyridyl to determine if reduced Fe is present (COE, 2010; USDA-NRCS, 2010).

Soil Physical Properties in Created Wetlands

Soil physical properties in created wetlands, such as soils bulk density (BD), texture, and structure are influenced by creation methods. Wetland construction frequently involves soil disturbances, which includes mass grading of the local landscape, and substantial stockpiling and redistribution of the upper soil horizons (Clewell and Lea, 1990; Stolt et al., 2000; Bruland and Richardson, 2005). A common wetland creation technique involves excavating upland soil to lower the new surface to at, or just above, the existing water table to achieve wetland hydrology. When the excavated soil is kept adjacent to the site to minimize transportation costs, this often leads to steep embankments bordering the wetland site, resulting in a lack of ecological transition zones (Haering et al., 1994; Bergschneider 2005). This method of construction often results in a finer surface texture due to exposure of clay rich subsoil horizons that are subsequently compacted by equipment. However, in a Pennsylvania wetland study, the authors found that that clay content at 20 cm in created wetlands was significantly lower than in the reference wetlands (Bishel-Machung et al., 1996). Bishel (1994) found that soil textures in created wetlands had a higher percentage of sand and concluded that this is “typical of wetlands developed from excavated upland substrates”. Compaction of soils is also intentional at many wetlands that are built with a “perching design” to induce epiaquic conditions and minimize net groundwater losses. Due to a lack of pre-construction groundwater monitoring, combined with regulatory oversight policies on water budgeting procedures, many wetland designs have historically tried to limit net groundwater losses by creating highly impermeable subsoil conditions through intentional soil compaction (Whittecar and Daniels, 1999). This design can be stressful for vegetation because roots may not be able to penetrate the perching layer, the roots may be more prone to drying out, and shallow roots may be more vulnerable to extreme weather events (Daniels et al., 2005). These differences in physical properties, particularly BD, vary between created and natural wetlands, and would be expected to affect other wetland properties such as OM accumulation and microbial activity. Water table levels between reference and mitigation wetlands may be affected by differences in soil texture between the wetlands. The differences in soil texture may control the hydrologic response to additions and losses of water, as the connected macropores in sandy textures transmit water more quickly than micropores in clayey textures (Hunt et al., 1999; Stolt et al., 2000; Brady and Weil, 2017).

Soil structure, like other soil properties, can also be influenced by wetland creation methods. Compaction during construction can result in a traffic pan with platy soil structure, which may pose problems for plant roots and water infiltration (Fajardo, 2006). Construction related compaction reduces strength of soil structure and associated macropores, which affects how the soil holds water (McIntyre, 1974; Petru et al., 2013). Over time, soils in created wetlands may develop stronger soil structure compared to initial conditions. More research is needed to quantify changes in soil structure (size, grade, and shape) over time related to additions of OM and any related response of hydrophytic vegetation parameters.

Soil physical properties are important to the success of created wetlands because these properties may affect both wetland vegetation (e.g. root-limiting compaction) and hydrology (e.g. presence of root-limiting compaction). More research on created wetland soil physical properties, especially years after initial creation, is needed to ensure future mitigation success.

Soil Organic Matter

Numerous studies have shown the importance of OM additions to enhance created wetland functions. The amount of OM decomposition and associated nutrient cycling is correlated with wetland soil redox potentials (Eh) (McLatchey et al., 1998). Adding organic amendments can increase soil aggregation, porosity, water holding capacity, soil moisture content, and phosphorous (P) sorption index (Stauffer and Brooks, 1997; Bruland and Richardson, 2004). Increasing soil OM causes a hydric soil to have a high water holding capacity, and the humates glue particles into aggregates that lead to the formation of soil structure (Buol et al., 1997). Examples of organic amendments include leaf and lawn compost, food processing waste, and forest products (Stauffer and Brooks, 1997). In the Southeastern US Coastal Plain, it is often the case that when constructing a wetland, the surface horizons are excavated to expose finer textured high BD, nutrient-poor subsoil. These conditions can limit growth of hydrophytic plants needed to meet vegetative criteria for a wetland (Bruland and Richardson, 2004). Organic matter additions can decrease soil BD and restore other soil properties such as low redox potential needed for hydrophytic plants to compete and survive (Bruland et al., 2009).

There is a slower rate of soil OM accumulation and distribution throughout the soil profile in early years of created wetland development. This is because younger wetlands do not have the overall plant community root and litter inputs that are needed for large OM accumulations (Ballantine and Schneider, 2009). One study estimates that it would take 300 years for soil in a newly created depressional, palustrine wetland to accumulate the same C in the top 0-5 cm as a natural wetland (Hossler and Bouchard, 2010). Another study used high OM salvaged marsh surface soil from a donor freshwater wetland to vegetate experimental plots in a created palustrine wetland (Stauffer and Brooks, 1997). This study also used leaf litter compost. After two growing seasons, the plots that were treated with the salvaged marsh surface contained more hydrophytic vegetation than the control plots. It was also found that the salvaged marsh surface added significant amounts of nutrients to the soils (such as higher nitrate-N). The leaf litter compost also added nutrients and increased soil moisture, which helped the survival of the lurid sedge (*Carex lurida* Wahlenb) that was planted in the plots. The plots with the salvaged marsh surface and composted leaf litter compost had significantly higher OM than control plots, but still less than levels found in natural wetlands. However, the plots with the organic additions had increased plant cover, species richness, density, and plant survivorship (Stauffer and Brooks, 1997).

Bruland and Richardson (2004) studied the effects of topsoil additions on created wetland soil properties. The purpose of their study was to evaluate soil property development in 11 created wetlands in Virginia ranging from 4 to 16 years since creation, focusing on non-tidal forested wetlands in the Coastal Plain. The sites either had at least 15 cm of topsoil added, or no topsoil. Hydrologic gradient (wet, intermediate, and dry) and topsoil status were also tested. Soil OM was shown to be an important indicator of soil quality because it had significant correlations with all of the other measured soil properties (moisture, BD, water holding capacity, P sorption index, and microbial biomass). The sites receiving topsoil had higher mean moisture, soil OM, and P sorption index, while the site that had the lowest mean moisture and soil OM did not have topsoil added. The authors recommended that sections of created wetlands with “intermediate elevation and hydrology” should be amended with OM. They postulated that dry sections of their wetland did not accumulate soil OM because of rapid aerobic decomposition. The sites with additional topsoil/OM had improved soil conditions that made it more likely to meet COE wetland hydrologic and vegetative criteria (Bruland and Richardson, 2004).

A study by Wolf et al. in 2011 looked at the development of soil properties and N-cycling in non-tidal created freshwater wetlands of varying ages, and natural reference wetlands. Their study produced a model that contained total organic carbon (OC), total nitrogen (TN), BD, and gravimetric soil moisture to evaluate soil condition. There was also a soil condition model developed for soil texture that contained average particle size diameter, sand and clay contents and Eh. Overall, the natural wetlands and the older constructed wetlands had higher soil condition scores. The youngest wetlands had the highest BD, while the older and natural wetlands had lower bulk densities. Texture of the soils varied independently from total OC, TN, moisture content, BD, and age. Three of the four created wetlands in this study were amended with topsoil when constructed. Previous comparison studies by Bishel-Machung et al. (1996) and Shaffer and Ernst (1999) did not study sites where topsoil was added and found that soil OM increased towards that found in natural wetlands with age (after three to five years or six years, respectively). This led the authors to conclude that "the addition of topsoil may be necessary for proper soil development" (Wolf et al., 2011).

Without OM additions, created wetland soil properties may require many years to resemble those of natural wetlands. A study by Hossler and Bouchard (2010) examined five created wetlands that were three to eight years old, and four natural wetlands. One of the created wetlands was treated as an outlier because of its history and site properties. The outlier had C and soil physical properties more typical of natural wetlands. This wetland had received organic-rich wetland soil re-applied during construction. Overall, the above-ground biomass, SOC, and mineralizable C were found to be significantly lower in the created wetlands than in the natural wetlands (Hossler and Bouchard, 2010). The exception to their model to estimate the amount of time it might take for the created wetlands to reach properties similar to natural wetlands was the one created wetland that received organic-rich topsoil during construction. This wetland had improved soil properties in the top 0-5 cm, but the organic addition did not have an impact on the 5-20 cm soil horizon or aboveground plant biomass. The soil physical properties formed more quickly than SOC accumulation (Hossler and Bouchard, 2010).

Overall, previous research suggests that topsoil and OM amendments help created and restored wetlands reach the functions of natural wetlands in less time than when no amendments are used during wetland creation and soil reconstruction. The addition of OM also promotes the growth of wetland indicator species (Bruland and Richardson, 2004).

Soil Redoximorphic Features

Redoximorphic features (or "redox features") are certain characteristics that allow for the identification of mineral wetland soils, and are "formed by the reduction, translocation, and/or oxidation of iron and manganese oxides" (Vepraskas, 1995). There are three requirements for a soil to develop reducing conditions. It must be saturated with water, contain respiring bacteria, and be largely depleted of dissolved O_2 in the soil water (Vepraskas and Faulkner, 2001).

Redox features are developed through microbiological processes, and their rate of development depends on three conditions:

1) The soil must have "sustained anaerobic conditions" (Vepraskas, 1995), which means saturated with water to prevent O_2 from the atmosphere entering soil pores.
2) The soil temperature should be above 5˚ C, otherwise biological activity slows or ceases.
3) A source of decomposable organic C (organic matter) which is a substrate for microbes, must be present in the soil.

Redox feature forming processes are dominated by redox chemistry but are also connected through other soil-forming processes that are complex and interacting (Fiedler and Sommer, 2004). The time needed for microbes to reduce Fe after saturation and anaerobic conditions form depends on the soil's OM source, if there is moving water, and the soil temperature (Vepraskas, 2001). The amount of depletions is related to the length of time a soil is reduced and is not directly related to the length of time that the soil is saturated (Vepraskas, 1992). According to Vepraskas, “the time required to form a reduced matrix has not yet been determined” (2001). However, the HSTS (National Technical Committee for Hydric Soils, 2007) requires two consecutive weeks of evidence of reduction during the growing season to meet the technical standard for hydric soil determination.

There are several types of redox features, which include redox depletions, reduced matrices, oxidized rhizospheres, redox concentrations, and relict features. Redox depletions are grey mottles with low chroma (≤ 2) and high values (≥ 4). This also includes clay depletions, which contain less Fe, Mn, and clay than surrounding soil. Redox depletions are formed through gleization, which is the reduction of ferric (Fe^{+3}) to soluble ferrous (Fe^{+2}) iron. Flooded soils also exhibit reduction of oxidized manganese (Mn3+ or Mn4+) to soluble Mn2+. Soils with an overall gray, greenish-blue, or blue-grey color have a reduced (or gleyed) matrix. A reduced matrix is a soil that has chroma ≤ 2 and value ≥ 4 because of the presence of Fe^{+2}, which when exposed to air, oxidizes and changes color. The reduced, soluble forms of Fe and Mn can be leached out of a soil, leaving the natural grey color of the soil matrix, which is a gleyed matrix.

An oxidized rhizosphere, also called an oxidized pore lining, is another type of redox feature. Wetland plants can transport O2 below ground through their roots, which creates larger pools of oxidized iron, and stimulates iron reduction. The concentration of oxidized iron on plant roots significantly varies between plant species (Sutton-Grier and Megonigal, 2011). The formation of redoximorphic features in the rhizosphere is influenced by bacteria. Weiss et al. (2003) found aerobic, Fe^{+2} oxidizing bacteria on 25 different wetland plant species. Oxidation and reduction of Fe can occur in the rhizosphere simultaneously, and both are mediated by bacteria. The iron cycle in the rhizosphere may be more active than in surrounding wetland soil because of more available O_2, labile carbon, and poorly crystalline Fe^{+3}. Poorly crystalline Fe^{+3} is readily reduced by Fe^{+3} reducing bacteria (Weiss et al., 2003).

Redox concentrations "form slowly over time by repeated episodes of Fe oxidation at the same points in the soil, such as at the interiors of peds where oxygen is entrapped when the soil saturates" (Vepraskas, 2001). There are three types of redox concentrations: nodules and concretions, which are firm or extremely firm, irregularly shaped, and have diffuse boundaries; masses; and pore linings. Concentrations form in soil that is periodically saturated. Concentrations are zones of oxidized Fe with an orange or reddish-brown color. Oxidized Mn, which is a dark reddish-brown to black color, can also form concentrations (Mitsch and Gosselink, 2007).

In wetlands that are created by excavation, redox features may be found at the surface that are not related to current day conditions but were formed at depth in the past. These are known as "relict features". A relict redoximorphic feature is a feature in the soil that formed in the past while the soil was wet, but still persists in the soil where it wouldn't form today. Relict features include redox depletions or redox concentrations. If identified as a current feature, these relict feature lead to an interpretation that a soil is wetter than it actually is. This hydrology change could be, for example, natural or artificial drainage. It is important to know when a soil's hydrology has changed because if the reduction features are relicts, the soil may no longer qualify as a jurisdictional wetland (Vepraskas, 2001). There is a lack of literature that shows what happens to deeper formed redox features over time that are brought closer to the soil surface.

Redox features form different patterns in sandy textured soils vs. in finer textures. In sandy soils, depletions and concentrations do not necessarily have a consistent relationship to macropores or aggregate (ped) surfaces (if any exist). This is because soil water and air can move readily through the pores and matrix as opposed to a finer textured soil where the macropores between peds convey soil and water and the ped interiors are largely isolated domains. A common redox feature in sandy soils is oval depletions within the matrix; this is because the larger macropores in sandy soils are not as well defined stable as the macropores associated with ped faces in loamy and clayey soils. Thus, many of the sandy (S) indicators for hydric soils rely on OC accumulation and distribution. This is also due to fact that many sandy soils lack significant Fe and Mn to form depletions and concentrations and are low in clay content so that OC is dissolved into forms that can move in solution and reconcentrate as organic bodies or ped coatings, etc. (Vepraskas, 2001).

Limited published studies are available on the rate of redox feature formation in created wetlands. In an early study (Vepraskas et al., 1999), hydric soil formation was investigated in a created marsh wetland in Illinois. After the deep marsh with silty clay loam soil texture was constructed in June 1989, it was continuously flooded during the growing season. Two transects of four plots each were described three and five years after the wetland creation. Transects included the marsh plots, edge plots, and upland plots. During this time, HSFI's formed in the marsh plots, edge plots, and in some plots transitioning to uplands. At the wetland edge, it took four years for the F3- Depleted Matrix indicator to form. The depleted matrix indicator was present in all of the edge plots by the fifth year. The authors concluded that the depleted matrix indicator (F3) can form within five years and was the fastest indicator to form at their site. During sampling in 1994, colors with chroma 2 or less were found in August but not in May in the Bt1 and Bt2 horizons. This was a small change in color, but large enough to determine whether or not a soil met the field indicator. Overall, landscape position and hydrologic regime affected the amount of color change in the soils, and the soils in the marsh plots demonstrated the largest change in color (Vepraskas et al., 1999). However, sandy soils with little or no Fe would have less potential for color change.

He et al. (2003) showed that an average of 21 days of consecutive saturation is sufficient for the reduction of Fe in some soils (as shown by Eh measurements). Longer or shorter amounts of saturation are needed in other soils due to differences in OC, temperature, and landscape position. This time period may also be texture dependent and vary based on the kind and amount of OM near the surface.

Meek et al. (1968) reported the effects of temperature, flooding time, and OM addition on Eh and the generation of soluble reduced Fe and Mn. Their study showed that adding OM increased the amount of Fe and Mn in the soil solution at a depth of 10 cm. It was found that without the addition of OM, longer flooding times (up to 96 hours) did not significantly decrease the Eh or increase the amount of Fe and Mn in solution. This study shows the importance of labile OM in the development of reducing conditions in flooded sandy soils.

Soil Nutrients

When a created wetland cannot provide essential nutrients (particularly N and P) at high enough levels, the wetland may not achieve ecosystem functions equivalent to local natural wetlands (Craft et al., 1991; Langis et al., 1991). Craft et al. (1998) reported that it may take some created marsh wetlands 15-30 or more years to develop total-N and SOC pools equivalent to that of natural wetlands. This study, which included three organic soils and two mineral soils, also found that N, P, and SOC pools were greatest in irregularly flooded marshes, compared to regularly flooded marshes. The soil nutrient pools increased with increasing marsh age and extent of saturated hydroperiod. In regularly flooded tidal marshes, more N, P, and C are exported by tidal action than in irregularly flooded marshes (Craft et al., 1998; Hackney and de la Cruz, 1982).

An important ecosystem function of wetlands is N retention and removal from surface and groundwater, an excess of which is a pollutant. Wetlands remove N primarily through denitrification, N sedimentation in organic forms, and by uptake by wetland plants (Saunders and Kalff, 2001). Created wetlands are designed to replace natural wetlands, and so they are generally assumed to provide N retention and removal because these are important services provided by the natural wetlands (Wolf et al., 2011).

Soil conditions (total OC, TN, BD, and gravimetric soil moisture) can be a significant positive predictor of denitrification and N-mineralization potentials. Also, net nitrification rates increase with constructed wetland age. In the study by Wolf et al., natural wetlands had the highest nitrification rates, the 7- and 10-year-old created wetlands had lower rates, and the three- and four-year-old wetlands had the lowest rates (2011). Nitrification requires oxidized conditions, so the lower BD and therefor higher porosity of older wetland soils in the study, along with higher TC, facilitated nitrification. Ammonification was found to be only marginally influenced by soil condition. Ammonification was positively correlated with total OC and total C sedimentation. Denitrification potential increased with soil moisture, total OC, and TN, and decreased with BD. In general, the younger created wetlands in the study had lower ammonification, nitrification, and potential denitrification rates than the natural wetlands and the older created wetlands. This study found a close link between the soil condition, which is made up of age-related soil properties, and N cycling. An appropriate way to assess function of a created wetland may be monitoring soil properties that are age-related, such as soil OM or OC, because these influence other important biogeochemical properties. Testing for soil OM and OC is more efficient and cost effective than testing each component process of the N cycle (Wolf et al., 2011).

Microtopography

Microtopography refers to local elevation changes on a soil surface. This feature is common in natural wetlands and forests (Bruland and Richardson, 2005). Sources of microtopography include sediment accumulation, erosion, tree fall, root growth, litter-fall, animal activity (Bruland and Richardson, 2004), and channeling during flooding (Stolt et al., 2000). Overall, the presence of microtopography improves plant and animal diversity, and creates heterogeneous soil and microclimate conditions for natural plant colonization or survival following planting (Titus, 1990; Vivian-Smith, 1997; Roy et al., 1999; Bruland and Richardson, 2005; Pennington and Walters, 2006). Therefore, development of microtopography may be important to created wetland management. In a study of three constructed wetlands and their adjacent natural wetlands, the constructed wetlands "had 40 to 60% less of an elevation change across the entire area than the reference wetlands". The natural reference wetlands had much more microtopographic variability. The constructed wetlands, which were 4- to 7-year-old, were assumed likely to gain more relief over time from "natural cutting and depositional processes" (Stolt et al., 2000). There is a lack in the literature regarding specific microtopographic effects on soil physical properties and vegetation in created wetlands.

Winton and Richardson (2015) measured greenhouse gas emissions and soil properties at the Charles City Wetland (CCW) experiment in the Coastal plain of Eastern Virginia and related the results to the plot elevations. This wetland site and plots will be studied in the experiment escribed later in this dissertation. At the CCW, Bergschneider (2005) found a positive relationship between plot surface elevation and a range of OM loading rates. The OM amendment applied in July 2002 was a mixed wood and yard-waste compost at five treatment levels (treatment 1 = 0 Mg ha^{-1}, treatment 2 = 56 Mg ha^{-1}, treatment 3 = 112 Mg ha^{-1}, treatment 4 = 224 Mg ha^{-1}, and treatment 5 = 336 Mg ha^{-1} on a dry weight basis). The OM was not incorporated completely into the soil at the two higher rates, which caused the differences in plot elevation (Bergschneider 2005). Winton and Richardson (2015) found that ten years after creation, elevation differences between plots were less pronounced in 2012 than in 2005 (Bailey et al., 2007), which may be due to more rapid oxidation of OM in the plots with originally higher loading rates. The differences in plot elevation due to OM loading rate did not affect seasonal greenhouse gas patterns, and there was no significant relationship between methane emissions and OM loading rate (Winton and Richardson, 2015). This methane emissions result contrasts with the findings of Ballantine et al. (2014), which found that higher OM loading rates increased water retention in the soil, which made favorable conditions for methanogenesis (the production of methane by microorganisms). Winton and Richardson (2015) stated that the OM amendments at CCW “may have had the opposite effect on soil moisture because of a slight mounding effect”.

Microtopographic effects were studied in another Virginia Coastal Plain wetland, the Weanack Wetland Experiment (WWE). The WWE is a sandy tidal forested wetland on the James River created in 2003 as a mitigation site. This is the same wetland site and plots that will be studied in the experiment proposed in this paper. There are five soil treatments that were applied in 2003: a fertilized control; 78 Mg ha^{-1} compost; 156 Mg ha^{-1} compost; topsoil plus 78 Mg ha^{-1} compost; and topsoil only. Microtopography (one pit and mound per plot, 75 cm wide each) was installed in 2004. In 2007, three years after bald cypress were planted, there was higher root count and greater root length in mounds than in directly adjacent pits or on level ground (Dickinson, 2007). Adding mounds to a wetland surface during creation may increase below-ground productivity. After the tenth growing season of the bald cypress at WWE, height, trunk diameter at 10 cm, diameter at breast height, and basal trunk swelling factor of the bald cypress were measured. Pietrzykowski et al. (2015) measured the effect of the microtopography on the bald cypress (*Taxodium distichum* [L.] Rich.) planted in three microtopographic positions (pit, mound, level). After 10 years of growth, bald cypress that were growing in pits were more likely to be in dominant and co-dominant ecological positions. Tree height, diameter at breast height (DBH), diameter at 10 cm, and basal trunk swelling of bald cypress trees were significantly greater in pits (Pietrzykowski et al., 2015).

Wetland Vegetation

Definitions

Hydrophytes are wetland plants that have adapted to living in flooded soils. There are three groups of plant adaptations- structural, physiological, and whole plant strategies. Structural adaptations include: aerenchyma tissue, which is a type of plant tissue with large air spaces to transmit oxygen through the plant to the roots; adventitious roots, which form on the stem above the anaerobic zone and function in an aerobic environment; and pneumatophores, which improve aeration and gas exchange to the roots (Scholander et al., 1955). Wetland plants have physiological adaptations to deal with not only anoxia (lack of oxygen) in wetland soil, but also for accumulations of reduced (toxic) forms of elements such as Fe, Mn, and S. Example of physiological adaptations include rhizosphere oxidation (which result in oxidized pore linings), lower water uptake, and altered nutrient absorption. Whole plant strategies that certain wetland plants have adapted include: delayed or accelerated flowering to produce seeds during the non-flooded season; the production of buoyant seeds and seedlings; rapid juvenile growth rate; and a large seedbank, particularly of annual or flood-intolerant species (Mitsch and Gosselink, 2007).

Plant species have varying tolerances of soil saturation and inundation in different regions. Each geographic region in the United States has a regional supplement that lists different wetland plant species and their indicator status. Table 1.1 lists the different indicator categories. For a species to be classified as hydrophytic, it must have an indicator status of OBL, FACW, or FAC (COE, 2010). Within a wetland, the vegetation is divided into strata that are sampled separately. The five strata are trees, saplings, shrubs, herbs, and woody vines. Table 1.2 defines these five strata. Alternatively, four strata may be used- trees, saplings/shrubs, herbs, and woody vines (COE, 2010).

For jurisdictional purposes, hydrophytic vegetation is evaluated by the COE based on the plant community at a site, rather than the presence or absence of indicator species (COE, 2010). In the Atlantic and Gulf Coast region, there are three indicator tests to use in a stepwise approach. The first indicator is a Rapid Test for Hydrophytic Vegetation, which requires that dominant vegetation across all strata are rated some combination of OBL and FACW, based on a visual assessment. If this test isn't met, then the user moves on to the next indicator, which is a dominance test. This tests whether "more than 50 percent of the dominant plant species across all strata are rated OBL, FACW, or FAC". If hydric soil and wetland hydrology indicators are present, but the site fails the dominance test, then the user can test the third indicator. If the site lacks hydric soil indicators, wetland hydrology indicators, and fails the dominance test, then hydrophytic vegetation is not present (or the site is a "problematic wetland"). The third indicator is a Prevalence Index, which "is a weighted-average wetland indicator status of all plant species in the sampling plot, where each indicator status category is given a numeric code" (COE, 2010).

Table 1.1. Plant indicator status categories † (COE, 2010).

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

† Categories were originally developed and defined by the U.S. Fish and Wildlife Service National Wetlands Inventory and subsequently modified by the National Plant List Panel. The three facultative categories are subdivided by (+) and (-) modifiers.

Table 1.2. Wetland vegetation strata (U.S. Army Corps of Engineers, 2010)

Stratum	Definition
Tree	Consists of woody plants, excluding woody vines, approximately 20 ft (6 m) or more in height and 3 in. (7.6 cm) or larger DBH[†].
Sapling	Consists of woody plants, excluding woody vines, approximately 20 ft (6 m) or more in height and less than 3 in. (7.6 cm) DBH
Shrub	Consists of woody plants, excluding woody vines, approximately 3 to 20 ft (1 to 6 m) in height.
Herb	Consists of all herbaceous (non-woody) plants, including herbaceous vines, regardless of size, and woody species, except woody vines, less than approximately 3.4 ft (1 m) in height.
Woody vine	Consists of all woody vines, regardless of height.

[†] Diameter at breast height

Establishing Vegetation in Created Wetlands

There are several ways commonly employed to establish vegetation in restored and created wetlands. One way that has been used in restored wetlands is a passive approach (Galatowitsch and van der Valk 1996; Barton et al., 2004). This consists of restoring wetland hydrology through breaking drainage tiles and plugging drain outlets and ditches. Seed dispersal and natural colonization from remnant seeds banks will establish the wetland plant species if the restored hydrologic conditions can favor these species and exclude upland species (Mitsch and Wilson, 1996). This passive revegetation, if successful, reduces the need for seeding or multi-species plantings that are more expensive. However, planting may be necessary to obtain populations of certain species that propagate through means other than seeding, such as rhizomes (De Steven and Sharitz, 2007). This approach can also be complicated by persistence of invasive and non-native wetland species such as reed canarygrass (*Phalaris arundinacea* L.) or common reed (*Phragmites australis* [Cav.] Trin. ex Steud.).

Soil physical properties (such as BD, OM, and texture) are related to the success of plant community development in created wetlands (Ballantine and Schneider, 2009). In constructed wetlands, plant community development is negatively affected by the use of heavy machinery, which damages soil structure and increases BD (Stolt et al., 2000; Bruland and Richardson, 2004; Ballantine and Schneider, 2009; Hossler and Bouchard, 2010). A recent study by Dee and Ahn (2012) investigated plant community development related to soil properties in wetlands in the northern Virginia Piedmont. The four study sites were created wetlands that raged in age from three to 10 years. Vegetation parameters measured included percent cover, and biomass, while soil parameters included gravimetric soil moisture, BD, soil OM, and pH. Site age in this study did not appear to relate to overall site development success because soil and vegetation developmental rates varied more within than among sites. Plots with greater OM, lowed BD, more neutral pH, and higher soil moisture were associated with higher plant diversity, total and volunteer cover, lower above-ground biomass, and seeded cover. The species that were planted in the wetlands, such as *Juncus effusus* L. and *Scirpus cyperinus* (L.) Kunth, produced more above-ground biomass than volunteer species and tended to dominate the areas with lower soil OM and higher BD in each wetland. On the other hand, the areas in the wetlands with higher soil OM and lower BD had higher plant community diversity and quality. This was also associated with an increase in volunteer species (Dee and Ahn, 2012).

Biomass

Biomass refers to the total mass of living plants in a given area. Soil structure, among other factors, may have an effect on plant biomass. Hossler and Bouchard (2010) found that above-ground biomass, was higher in wetland soils that were higher in soil macroaggregates, and lower in microaggregates. Wetlands that do receive organic amendments may require a shorter time to reach properties similar to natural wetlands (Hossler and Bouchard, 2010).

Wetland plants produce stem biomass and foliar litter above the soil surface, and they also produce significant biomass below-ground. Fine roots [diameter of ≤ 3 mm, some studies use ≤ 2 mm

(Baker et al., 2001) die annually in large amounts, and may contribute a similar amount of biomass as above-ground biomass (McClaugherty et al., 1984). To obtain an accurate measure of C balance in the research sites, this project included below-ground biomass, herbaceous above-ground biomass, litter, and sapling+ tree biomass estimates.

Generally, in rooted aquatic plants, a decrease in nutrient availability results in increased root biomass (Barko et al., 1991). Past studies have shown that a lower availability of N and P increased root:shoot ratio in aquatic plants, including *Elodea canadensis* Michx., E. nutallii (Planch.) H. St. John, and *Lagarosiphon major* Ridl. Moss ex. Wagner (James et al., 2006). A similar response is also common in upland vegetation (Hutchings and John, 2003). Hussner et al. (2008) evaluated the effect of water level and nutrient availability on a wetland plant, *Myriophyllum aquaticum* (Vell.) Verdc., in a greenhouse. Nutrient availability was found to have a positive relationship with root density, and a negative relationship with root:shoot ratio.

Neatrour et al. (2005) examined "the relationship between soil nutrients and fine-root biomass (Mg ha^{-1}) in forested wetland ecosystems". Root biomass was compared across three wetland types: depressional swamps, dominated by pond cypress (*Taxodium ascendens* Brongn.) and swamp tupelo (*Nyssa biflora* Walter); river swamp sloughs, dominated by bald cypress; and floodplains, dominated by water tupelo (*Nyssa aquatic* L.). Patterns in root biomass and soil nutrients were measured in plots in each wetland. Within the combined wetlands, there was a negative correlation between fine-root biomass and three soil nutrients- NO_3-N, NH_4-N, and PO_4-P (Neatrour et al., 2005).

Root biomass may also be affected by hydrology. A study by Koontz et al. (2013) found that rice cutgrass (*Leersia oryzoides* [L.] Sw.) in a continually flooded soil had a significantly higher aboveground to belowground biomass ratio compared to rice cutgrass in a partially flooded soil, and the control. Neatrour et al. (2005) found that floodplain swamps had 2.5 to 3 times less fine-root biomass than the depressional swamps or river swamp sloughs. The river swamp slough sites dried faster during the experiment than the depressional swamps, and “more C may have been allocated to fine roots to facilitate water uptake during drought conditions rather than in response to soil nutrient availability” (Neatrour et al., 2005). In another study, bald cypress saplings that were periodically flooded had greater root:shoot ratios than bald cypress that were continuously flooded (Megonigal and Day, 1992). Different species respond differently to flooding in terms of root growth, and this may be due to the timing of root production. For example, cherrybark oak (*Quercus pagoda* Raf.) root production is early in the year, so flooding in the spring negatively impacts root growth. Overcup oak (*Quercus lyrata* Walter) begins root production later in the year, which allows it to avoid flood stress on root growth. Overall, longer periods of inundation resulted in lower root biomass and lower root production (Burke and Chambers, 2003).

Bailey et al. (2007) found a lack of correlation between plant biomass and OM loading rate at a palustrine wetland in Virginia (the CCW site studied here) and suggested that biomass may not always be a useful indicator of the wetland creation success. Organic matter additions may improve function of a created wetland by increasing soil fertility and moisture holding capacity, driving essential wetland redox process, and by decreasing BD and temperature fluctuations. However, above-ground plant biomass may not reflect these changes (Bailey et al., 2007). Ballantine et al. (2012) also failed to find a significant effect of organic amendment on plant biomass or diversity. Four treatments and a control were applied to restored palustrine wetland soil, and the soil properties were measured after three years. The treatments applied were straw, topsoil, a 50:50 mix of straw and biochar, and biochar alone. They found that the plant biomass did not differ among treatments or sites three years after restoration, possibly because the OM applied was coarse, therefore more time would be needed for the OM to decompose and mineralize nutrients into plant available forms. However, the addition of the amendments did increase soil C and decrease BD, and the topsoil amendment significantly increased total soil N (Ballantine et al., 2012).

Vegetation Diversity

Vegetation diversity (number of species per area) in created wetlands can be strongly affected by the initial seeding or planting species selection and procedures. Reinartz and Warne (1993) looked at 11 created depressional wetlands that were allowed to be naturally colonized, and five wetlands that were intentionally seeded with 22 species. The diversity in the colonized wetlands increased with age, size, and proximity to nearest wetland seed source. In the naturally colonized wetlands, Typha spp. made up 15% of vegetation in wetlands one year old, and 55% in wetlands three years old. The authors noted the possibility of Typha spp. monocultures over time in colonized wetlands. In contrast, the seeded wetlands were found to have higher species diversity two years after planting. The amount of Typha spp. cover in the planted sites was lower than in the colonized sites (Reinartz and Warne, 1993).

Some wetland scientists may disagree that a diverse planting at creation is the best way to achieve wetland function later. Odum (1987) suggested that planting later successional species that supposedly have a high value to wildlife might be an "expensive waste of time" in many freshwater wetland sites. Mitsch and Gosselink (2007) state that natural successional processes should be allowed to proceed to develop a low-maintenance wetland. A strategy for this is to seed and plant as many native species as possible, and then allow natural processes to select for the native plants and weed out the invasive species and upland species (Mitsch and Gosselink, 2007).

Two wetlands in Ohio have been researched for over a decade (Mitsch et al., 2005; Mitsch and Gosselink, 2007). The wetlands are identical except that one was intentionally planted and the other was naturally colonized. Differences were found in the functions of the wetlands. The naturally colonized wetland had higher estimated values for C sequestration and amphibian production after a decade, while the planted wetland had higher estimated values for vegetation diversity. The authors concluded that whether to plant a created wetland or allow natural colonization depends on the end goal. For example, if vegetation diversity is the goal, then planting the wetland is likely to be beneficial. If C sequestration is the goal, then planting the wetland may be a waste of resources. However, from this research there does seem to be a long-term effect on diversity from intentionally planting appropriate species (Mitsch et al., 2005; Mitsch and Gosselink, 2007).

Mass Carbon in Wetlands

Metting et al. (1998) estimated that the potential global C sequestration in wetlands is 0.1-0.2 Gt C yr^{-1}. Estimates of dry-weight biomass per unit area of land and their change over time can be used by land managers to estimate C pools and fluxes on individual properties, by policymakers to estimate forest C dynamics at large scales, and by scientists to improve our understanding of C dynamics and sequestration (Jenkins et al., 2004).

Soil mass C is the estimate of the total mass of carbon within an area of soil, measured in Mg C ha^{-1}. Some studies may report mass C of an ecosystem as the below-ground biomass C, above-ground biomass C, litter C, and SOC combined. Global climate change, which includes elevated concentrations of CO_2 in the atmosphere, has led environmental scientists to realize the importance of soils as a significant terrestrial C sink (Minasny et al., 2014) when properly managed.

In one related study in Virginia, soil mass C per horizon was calculated at three soil depths for 10 mitigation and paired natural wetlands, and mass C followed a similar pattern as SOC percent (Fajardo, 2006). There were fewer significant differences between the mitigation and natural wetlands for mass C than OC percent, because of the much higher bulk densities in the subsoils than at the surface. Overall, the mass C for all three soil depths combined ranges from about 47 Mg C ha^{-1} to 176 Mg C ha^{-1}. However, the carbonates present likely raised the values in the subsoil for at least one of the sites, so a representative high value in the range is closer to 91 Mg C ha^{-1} where carbonates are not present. This shows that in general, the mass C in created wetlands in Virginia is less than the amount in natural wetlands, which average around 720 Mg C ha^{-1} in the contiguous U.S (Kern, 1994).

Carbon Sequestration

Organic carbon is part of the carbon cycle, which occurs in the atmosphere, oceans, soils, sediments, and rocks. Increased CO_2 and CH_4 in the atmosphere lead to global climate change (Solomon et al., 2008; Myhre et al., 2014). Soils absorb and release these gasses in processes that include plant growth (photosynthesis) and decomposition by microorganisms. Processes that increase soil C storage can help mitigate climate change (Bliss et al., 2014; Minasny et al., 2014).

Carbon sequestration is an important wetland function. Because wetlands are created to mitigate wetland loss or damage of natural wetlands, it is important to analyze the functions of created wetlands. This includes measuring mass C in created wetlands, and C accumulation over time. Ecosystems store OC in living forms such as vegetation (shoots and roots) and the active microbial biomass, and in nonliving forms such as dead plant tissue, litter, and soil OM. In wetland ecosystems, the nonliving OC storage is higher than in other ecosystems and is considered an energy reserve for the ecosystem (Wetzel, 1992; Collins and Kuehl, 2001). Globally, SOC content is greater at higher latitudes and the tropics and decreases in the middle. This is due to lower temperatures with reduced decomposition at higher latitudes, and higher rainfall in the tropics (Minasny et al., 2014).

Carbon may be present in soils as inorganic carbon (e.g. carbonates) or in various organic forms (SOC). Soil inorganic carbon phases can include gaseous CO_2, dissolved CO_2, carbonic acid (H_2CO_3), bicarbonate (HCO^{3-}), carbonates (CO_3^{2-}), and solid-phase calcium carbonate (e.g. calcite) (Monger, 21014). However, inorganic carbon is rarely found in the surface of forested wetland soils of the humid eastern United States due to their lower pH and leaching history and is assumed to not be present unless detected by appropriate soil tests (effervescence in dilute HCl) or soil pH > 7.5. Where inorganic carbon is absent, SOC is assumed to be equal to total C.

In general, SOM includes plant and animal residues in various stages of decomposition (Soil Science Society of America, 2014; Collins and Kuehl, 2001). Depending on soil type and other factors such as the nature of dominant plant residues and climatic conditions, SOM consists of approximately 56% SOC (Nelson and Sommers, 1982). Soil organic matter also contains other elements (e.g. organic P and N).

It has been estimated that wetlands in the contiguous United States contain an average SOC content of 720 Mg C ha^{-1} (Kern, 1994). This average value includes Histosols and bog soils, which by definition have high OM contents, so the average SOC content in Virginia wetlands would be lower because Histosols are not a dominant soil order in the region.

Fajardo (2006) evaluated 10 mitigation wetlands in Virginia (including the CCW site), all of which were less than 5 years old at the time of sampling. Most of the wetlands were constructed by cutting into the subsoil. Eight out of the 10 wetlands had surface (0-15 cm) SOC that was limiting to plant growth (<2%). The two wetlands that had >2% OC were created using a fill method rather than a cut method. The OC in the surface soils of the wetlands ranged from 0.85% to 2.59%. A low OC percent in some of the wetland surface soils may be influenced by the young age of the sites at sampling (the soil with the lowest OC percent was two-year-old, while the site with the highest OC percent was four-year-old). In addition to the surface soil, subsoil OC was measured at depths 30-45 cm and 90-105 cm. At 30-45 cm, the OC percent ranged from approximately 0.17% to 0.62%. At 90-105 cm, the range was from 0.10% to 0.52%. It was noted that some of the values may have been high because of the presence of carbonates (Fajardo, 2006). These results also show that OC generally decreases with depth, as other studies have also shown (Cummings, 1999; Stolt et al., 2001). More research is needed for created wetlands that are greater than 10-yr-old, and whether initial amendments or vegetation have a lasting effect on SOC.

Biomass Carbon

Biomass C (g m−2) is the measure of C in above-ground plant tissue, excluding litter. Johnson and Rejmánková (2005) measured the C content in four wetlands in Belize, with the goal of determining whether agricultural practices were affecting adjacent wetland properties. The studied wetlands had varying soil type (sandy to clayey) and vegetation composition. Plants within the sampling area included Gulf Coast spikerush (*Eleocharis cellulosa* Torr.), cattail (*Typha* L.), and knotted spikerush (*Eleocharis interstincta* [Vahl] R. & S.). They found that plant C content (%) did not differ between wetland marshes that were adjacent to agricultural production, and marshes that were surrounded by forest. The plant C did vary by species- Cladium (a moss) had the highest plant C content, Typha had the next highest, and the Eleocharis species together had the lowest C content. The authors concluded that this reflects the cellulose content of the species (Johnson and Rejmánková, 2005), so plant C may vary more with species than other environmental factors.

Management Recommendations and Previous Specific Studies at Research Sites

A few aspects to consider when making recommendations for created wetland success include planting strategy (stock type and species), creation of microtopography, and soil amendments. Some research on the effects of these factors on soil and vegetation properties has been conducted in created wetlands.

Transplant shock may occur in plants introduced to a wetland. This can appear as stem die-back. Stem sprouting and root-suckering may also occur in response to a stressful environment. An option of avoiding transplant shock is to use more mature stock types, and to transfer the soil from the container with the root ball. This reduces the impact of compacted wetland soil and may also be beneficial if there are mycorrhizal associations in the container soil (Roquemore et al., 2014). The selection of plant species and stock type is influenced by ecological goals, budget, time constraints, and regulatory conditions. For example, for certain ecological functions that require mature trees within a short time frame, trees grown in 4L containers might be more beneficial than bare-root seedlings. Trees grown in 1-gallon containers are more expensive than bare root seedlings; however, they have a higher survival rate. Bare root seedlings can be planted at a higher density to offset the low survival rate, and for a lower cost than using trees grown in large containers (Roquemore et al., 2014).

The determination of an appropriate loading rate of OM and other soil amendments is an important management decision to consider. Bergschneider (2005) evaluated different OM loading rates at two experimental sites in the Coastal plain of Eastern Virginia (e.g. the same CCW sites studied here). There were five OM treatment levels: treatment 1 = 0 Mg ha^{-1}; treatment 2 = 56 Mg ha^{-1}; treatment 3 = 112 Mg ha^{-1}; treatment 4 = 224 Mg ha^{-1}; and treatment 5 = 336 Mg ha^{-1} on a dry weight basis. The 112 Mg ha^{-1} loading rate of yard-waste compost was optimal for creating hydric soil conditions and a positive hydrophytic vegetation response. This conclusion was made because the treatment led to improved conditions for the rapid development of HSFI's, and the overall growth of herbaceous and woody wetland vegetation. Higher rates could not be adequately incorporated into the soil, so these rates were not ideal for short term soil or plant growth effects. Over the long-term, higher rates of compost could potentially positively influence wetland soil and vegetation following full decomposition and near-surface SOM accumulation.

Bailey et al (2007) studied the vegetation at the same CCW experiments three years (two full growing seasons) after treatments were incorporated. Parameters measured include soil surface elevation, soil nutrients, plant assemblage composition and diversity, standing crop biomass, and woody vegetation development (total height, crown diameter, main stem diameter, and number of stems). The authors hypothesized that the plant communities would vary in species composition among the different OM loading rates, and that plant biomass and tree size would increase with loading rates. Bailey et al. (2007) also made soil C and TN measurements at CCW. The TN content of treatment 1 was lower than that of natural wetlands and was similar to TN contents of created wetlands that were not amended. In another study, Baker and Broadfoot (1979) reported that a surface OM concentration of 2% or less was an indicator for nutritional limitation for deciduous floodplain trees, and the average OM value of surface soil in treatment 1 was only slightly above this value.

At the CCW, Bergschneider (2005) found a positive relationship between plot surface elevation and a wide range of OM loading rates. This was due to the incomplete incorporation of the OM, which caused differences in plot elevation and relative aeration/redox (Bergschneider 2005). Results showed that soils under treatments 4 and 5 had higher redox potentials than soil under treatments 1, 2, and 3 (Daniels et al., 2005). The elevation effects indicated that some of the coarser compost fragments did not fully decompose three years after the initial application. Plant species colonization and survival was affected by the 11 cm difference in average elevation between treatment 1 and treatment 5 plots. The authors concluded that the OM in the high loading rate plots will break down over time, and elevation differences should decrease, which “has the potential to further homogenize plant species” (Bailey et al., 2007). Soil surface elevation, along with saturation and inundation, were more important than organic amendments in the early years of the CCW. The authors concluded that a more labile form of OM may result in a quicker plant response, and that “longer periods of time are necessary for coarse OM to decompose and mineralize nutrients such as N and P into plant available forms” (Bailey et al., 2007).

Microrelief or microtopography may also be important to wetland management. Although not a direct measurement of wetland function, microtopography can be used to compare functionality of created wetlands to natural reference wetlands along with other environmental conditions such as soil texture, pH, CEC and base saturation (Stolt et al., 2000). Dickinson (2007) found that incorporating microtopography had an overall positive effect on vegetation function in a created sandy tidal forested wetland on the James River in Eastern Virginia. Three years after bald cypress were planted and treatments were applied, there was higher growth (count and length) for live roots found in mounds than in directly adjacent pits or on level ground. Adding mounds to a wetland surface during creation may increase below-ground productivity, which would contribute to wetland soil OM accumulation. The bald cypress trees had increased basal swelling, height, and trunk diameters in the pits (Pietrzykowski et al., 2015). More research is needed on the effects of microtopography on older wetland tree species.

The past results of the study site reported by Dickenson (2007) and Pietrzykowski et al. (2015) mainly focused on wetland vegetation responses to the soil amendments (topsoil and compost) and constructed microtopography at the Weanack Wetland Experiment (WWE). WWE is a sandy tidal forested wetland on the James River created in 2003 as a mitigation site and is also studied here. The highest proportion of obligate wetland species per plot was produced by adding compost (1x or 2x). The lowest proportions of obligate wetland species, and the highest proportion of upland plants was produced by adding topsoil (1x compost +topsoil or topsoil). However, the treatment that produced the highest plant species diversity over the first three years was the non-amended sandy control. The topsoil used may have had a seed bank that introduced more upland and invasive species to the site. Dickinson (2007) concluded that an existing seed bank can be a disadvantage to the dominance of hydrophytic vegetation and species diversity. It was also recommended that if topsoil is added to a mitigation wetland, then the topsoil should come from a wetland environment, not an upland environment. Overall, based on her results two years after treatment application, Dickinson (2007) recommended that “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”.

Objectives and Dissertation Organization

Overall, my research was designed to contribute knowledge of the long-term effects of OM on created wetland soils. Existing literature shows that OM additions have positive effects on wetland soil properties after 5 years (such as decreased soil BD), but there is minimal literature available on the effects over longer periods of time, especially in forested wetlands. This research also informs the development of management recommendations for creating forested wetlands in the Coastal Plain on sandy and fine-textured soils. The objectives by chapter are as follows:

Chapter 2: Effects of Amendments and Microtopography on Created Tidal Freshwater Wetland Soil Genesis and Morphology

This chapter includes OM, topsoil, and microtopographic treatment effects on soil morphological properties (color, structure, and horizonation) at WWE. This includes soil genesis over time, using descriptions from 2005, 2007, and 2015. The overall objectives of this study were to analyze the long-term effects of amendments and microtopography creation on these soil properties 12 years after construction.

Chapter 3: Amendment and Microtopography Effects on Bulk Density and Chemical Properties in Created Tidal Sandy Freshwater Wetland Soils

The objectives of this study were to report long-term OM and topsoil treatment effects on soil physical and chemical properties (BD, OC, mass C, TN, plant-available nutrient content) at WWE. Additional objectives were to analyze changes in soil parameters from 2005 to 2015 by treatment to determine whether any treatments affected development of hydric soil characteristics since construction.

Chapter 4: Effects of Compost Amendments on Virginia Created Wetland Soils 14 Years after Application

This chapter includes soil genesis and morphology at CCW between 2003 and 2016, soil physical properties (texture, BD), and soil chemical properties (TC, mass C, TN, plant available nutrients). The objectives of this study were to analyze long-term OM treatment effects on soil properties, and changes in soil properties over time.

Chapter 5: Soil Organic Matter and Topsoil Amendment Effects on Mass Soil Carbon in Two Created Wetlands

This chapter includes soil mass C, litter C, and biomass C at both WWE and CCW. The objectives of this study were to determine long-term amendment effects (OM and topsoil at WWE; OM at CCW) on total mass C in soils, root biomass, litter, and woody biomass. Additional objectives were to develop amendment recommendations for created wetlands in the Coastal Plain.

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2. Effects of Amendments and Microtopography on Created Tidal Freshwater Wetland Soil Genesis and Morphology

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Abbreviations: BD: bulk density; DBH: diameter at breast height; HSFI: hydric soil field indicator; OC: organic carbon; OM: organic matter; TN: total nitrogen;

Abstract

Created wetlands used to compensate for wetland impacts often have lower organic matter (OM), less microtopography, and fewer hydric soil indicators than natural wetlands. Organic matter amendments improve initial soil properties, but long-term effects are seldom reported. This study describes soil properties in the upper 30-cm of a sandy, tidal, freshwater created wetland in the Coastal Plain of Virginia as well as their changes over time. During construction in 2003/2004, five treatments were applied (78 Mg ha^{-1} compost-wet, 156 Mg ha^{-1} compost-wet, 15 cm loamy topsoil plus 78 Mg ha^{-1} compost, loamy topsoil without compost, and control), pits and mounds were constructed, and initial soil colors were determined. Soil descriptions were made in 2005, 2007 and 2015. Soils that had topsoil applied developed soil structure in the surface and subsurface faster than the control and compost treatments. Over time, soils uniformly became darker (lower value and chroma) in A horizons, more gray (lower chroma) in C horizons, and increased in OC and TN content, regardless of treatment. Sandy soils developed a wider variety of HSFIs. Long-term treatment effects of loamy topsoil additions include greater horizon development and stability of HSFI but otherwise had no positive long-term effects in sandy created wetlands. In 2015, we measured color by microtopographic positions (pit, mound). Pits had lower color value (2.4) and chroma (1.9) than mound soils. Compost additions at these rates had no significant long-term effects in this tidal freshwater system. Microtopography treatments have long-lasting positive effects (increased TC and lower BD) on created wetland soil properties. We recommend adding pit and mound microtopography to created wetlands for increasing diversity of habitat.

Introduction

Development, road building, agricultural, and forestry land uses have reduced the extent of U.S. wetlands by over 50% (Dahl, 1990). Restoration and wetland creation have been used to offset losses since the 1980's (Mitsch, 1992; Atkinson et al., 1993; Allen and Feddema, 1996; Brown and Lant, 1999). Many wetland impact compensation efforts have involved restoration of hydrology to areas previously drained for alternate land use (e.g., agriculture, forestry; Brinson and Eckles, 2011). However, potentially restorable wetlands may not exist within the watershed or general area where mitigation is required, so creation of wetlands on upland sites may be necessary.

Creation of wetlands from former uplands is the most difficult type of wetland mitigation to successfully accomplish (Zedler and Callaway, 1999). Created wetlands frequently have not provided the same levels of essential ecosystem services as natural wetlands due to issues such as low organic or total carbon (TC) (Bishel-Machung et al., 1996; Whittecar and Daniels, 1999; Stolt et al., 2000; Fajardo, 2006), compaction (Bishel-Machung et al., 1996; Campbell et al., 2002), and limited rooting volume (Daniels et al., 2005). Considerable research has been conducted on wetland creation and differential outcomes, but additional research is needed to develop appropriate site and soil construction recommendations (Whittecar and Daniels, 1999; Daniels and Whittecar, 2004).

The surface and subsoil soil texture in created wetlands depends largely on how the wetland was created (e.g. excavation to subsoil, with/without topsoil additions, moisture conditions vs. traffic, remedial tillage, etc.). Created wetlands may have a finer particle size than natural wetlands if excavated to a clayey subsoil (Bt or Btg horizons) without replacing topsoil (Stolt et al., 2000), or may have a sandier and rockier particle size if excavated to a coarser subsurface C horizon (Bishel-Machung et al., 1996; Campbell et al., 2002). Sandy wetland soils also tend to have lower cation exchange capacity and water holding capacity than finer textured soils (Stolt et al., 2000).

Adding OM is potentially beneficial in created wetlands. Examples of organic amendments include leaf and lawn compost, food processing waste, and forest products (Stauffer and Brooks, 1997). Adding organic material can provide an extended source of mineralizable N and P for plant growth. Adding organic amendments can increase soil aggregation, porosity, water holding capacity, soil moisture content, and P sorption index (Stauffer and Brooks, 1997; Bruland and Richardson, 2004). Organic matter additions can decrease soil BD, increase the rate of reduction of Fe in anaerobic soils, and restore other soil properties such as low redox potential needed for hydrophytic plants to compete and survive (Bruland et al., 2009). Added OM serves as an electron source for Fe-reducing bacteria and can lead to redoximorphic feature formation within two years of wetland construction (Stolt et al., 1998).

Wetland creation often involves topsoil removal and stockpiling, and compaction when it is replaced. Bruland and Richardson (2004) found that created forested wetlands that received topsoil during construction had higher mean moisture, OM, and P sorption index, compared to sites without a topsoil amendment. Adding topsoil to a created wetland donated from a nearby wetland may improve moisture-holding and chemical properties beneficial to wetland vegetation, may contain a wetland seed-bank (including seeds that are ready to germinate), and can lead to a greater vegetation diversity than adding sterilized donor soil (Burke, 1997). McKinstry and Anderson (2005) found that treating created wetlands with donor wetland soil increased the number of plant species over time, vegetation coverage, and plant biomass. However, upland topsoil may not provide these benefits to created wetlands. Dickinson (2007) found that adding donor loamy upland topsoil contributed to the upland seed bank at the same site studied here, which increased the presence of invasive and non-native upland plants.

Redoximorphic (redox) features are used to identify mineral hydric soils, and include depletions and concentrations of Fe and Mn, reduced matrices, and oxidized rhizospheres (Vepraskas, 1995). The time needed for microbes to reduce Fe after saturation and anaerobic conditions depends on the soil's OM quantity and quality, water movement, and the soil temperature (Vepraskas, 2001). The amount of depletions is dependent on length of time a soil is reduced and is not directly related to the length of time that the soil is saturated (Vepraskas, 1992). Based on redoximorphic potential (Eh) measurements, an average of 21 consecutive days of saturation may be sufficient for the reduction of Fe in some soils (He et al., 2003). Longer or shorter lengths of saturation are needed in other soils due to differences in amount and location of OM, temperature, and landscape position, and possibly texture (Vepraskas, 2001). Without the addition of OM, saturation times up to 96 hours may not be enough to decrease the Eh enough for reduction of Fe and Mn (Meek et al., 1968). Adding OM to a silty clay soil was found to increase the amount of Fe and Mn in the soil solution in the upper 10 cm (Meek et al., 1968).

Redox features form different patterns in sandy textured soils than in finer textures. In sandy soils, depletions and concentrations do not necessarily have a consistent relationship to macropores or aggregate (ped) surfaces. Soil water and air can move readily through the macropores and matrix as opposed to a finer textured soil where the macropores between peds convey soil and water and the ped interiors are largely isolated domains (Vepraskas, 2001). Finer textured soils have large root channels that remain stable after a root has died and decomposed, so depletions forming around root channels will be a different shape in sands where the channel collapses (Vepraskas, 2001). Therefore, adding loamy topsoil to a sandy created wetland is expected to affect redox feature formation.

Hydric soil field indicators (HSFI) are a morphological method to identify hydric soils in created wetlands. The indicators are typically accumulations or redistributions of OM or OC noted by specific colors and textures, odor of a reduced S gas, and colors from depletions or accumulations of Fe and/or Mn (USDA-NRCS, 2017). The indicator F3 Depleted Matrix for fine textured soils has been documented forming within five years of wetland creation in a silty clay loam marsh in Illinois after continuous flooding during the growing season (Vepraskas et al., 1999). Sandy soils may be lower in Fe than loamy textured soils, which may limit development of HSFIs or slow their rates of development (Kuehl et al., 1997; Robinette et al., 2004; Rossi and Rabenhorst, 2015). It is unclear whether adding loamy topsoil and/or compost to a created sandy wetland may or may not increase the formation rate and amount of redox features and HSFI's.

Microtopography (irregular elevation changes on a soil surface) is a common feature of seasonally-saturated natural wetlands and forests (Bruland and Richardson, 2005). Sources of microtopography include sediment accumulation, erosion, tree fall, root growth, wood- and litter-fall, animal activity (Bruland and Richardson, 2005), and channel scour/deposition during flooding (Stolt et al., 2000). The presence of microtopography increases the numbers of plant species that can survive in a given wetland and thereby improves plant and animal diversity by creating heterogeneous soil and microclimate conditions for natural plant colonization or survival following planting (Titus, 1990; Vivian-Smith, 1997; Roy et al., 1999; Bruland and Richardson, 2005; Pennington and Walters, 2006). Microtopographic variations from treefall in wetlands include mounds that are usually slightly above the saturated soil surface and pits that remain saturated longer. Dickinson (2007) and Pietrzykowski et al. (2015) examined the effects of microtopography and soil amendments on bald cypress (*Taxodium distichum* [L.] Rich) planted in the same experimental wetland studied here. Two years after construction, bald cypress growing in pits were taller, had a larger diameter at breast height (DBH), and lower root biomass than bald cypress growing on mounds or level areas (Dickinson, 2007). After the tenth growing season, cypress that were growing in pits were more likely to be in dominant and co-dominant ecological positions. Tree height, DBH, diameter at 10 cm, and basal trunk swelling of bald cypress trees were also greater in pits (Pietrzykowski et al., 2015). Overall, these results suggested that installed microtopography (particularly pits) directly benefitted cypress growth.

Microtopography is typically eliminated during wetland construction due to extensive grading and soil reconstruction. Most created wetland designs also rely on strict control of local surface elevations to attain appropriate wetland hydrology and water depths, which also tends to limit local microtopography (Stolt et al., 2000; Daniels and Whittecar, 2004). However, replacement of microtopography may be important to created wetland management. In a study of three constructed wetlands and their adjacent natural wetlands, Stolt et al. (2000) reported that the constructed wetlands "had 40 to 60% less of an elevation change across the entire area than the reference wetlands". The constructed wetlands, which were four- to seven-year-old, were assumed likely to gain more relief over time from "natural cutting and depositional processes". However, windthrow events that create microtopography are less likely in newly created wetlands because of the absence of large trees and therefore must be created during site/soil reconstruction.

Previous research shows the benefits of adding soil OM (such as compost) to created wetlands within a few years after construction. Adding topsoil may improve soil properties of sandy created wetlands, especially if the topsoil comes from a nearby wetland. However, there is a lack of literature on long-term effects of compost and topsoil amendments on created wetland soil properties. Microtopography affects soil physical and chemical properties and processes but the long-term influence on differential soil properties has not been studied in created wetlands. Therefore, the overall objectives of this study were to compare the long-term effects of soil amendments (compost and loamy topsoil) and microtopography creation on soil properties in a sandy tidal freshwater created forested wetland 12 years after construction.

Materials and Methods

Site Description and Experimental Design

The Weanack Wetland Experiment is a 2.74 ha created wetland located immediately south of Shirley Plantation on the James River floodplain in the Virginia Coastal Plain in Charles City County at 37.330922N, 77.265518W (Figure 2.1). Average annual total precipitation (almost all rainfall) is 109 cm, with about 61 cm of the total falling between April and September (Hodges and Thomas, 2005). The hydrology is tidally influenced with respect to daily groundwater fluctuations but ponding rarely occurs during the growing season. Some inundation occurs during the non-growing season, and the entire wetland occasionally floods up to 1 m deep during strong winter storms and fall hurricanes. The soils at the site are repeatedly saturated within 15 cm of the surface most days of the year.

The pre-treatment soil formed in an upland deposit of dredged sand from the James River which overlaid native hydric soils by > 3 m. The excessively drained soil was similar to the Lakeland soil series (Thermic, coated family of Typic Quartzipsamments). The site was excavated and graded to a near level configuration in late 2003 and included a range of target vegetative communities including forested, shrub-scrub and emergent. The final design elevation of the experimental area discussed here is near sea level, ranging from 1.01 to 1.13 m above mean low tide in an adjacent (~ 50 m away) open water cove. By 2015, the soil had become a poorly drained soil estimated to be a member of the dredgic, thermic family of Anthroportic Psammaquents (Soil Survey Staff, 2014b; John M. Galbraith, pers. comm.) which was closest in morphology and properties to the Osier series (siliceous, thermic family of Typic Psammaquents).

The experiment was established as a completely randomized design (Figure 2.2). There were five treatments with four replicates each, except the control, which had five replications (treatment 1 = control, treatment 2 = 78 Mg ha^{-1} compost, treatment 3 = 156 Mg ha^{-1} compost, treatment 4 = 15 cm topsoil plus 78 Mg ha^{-1} compost, treatment 5 = 15 cm topsoil only). Plots that received 15 cm of stockpiled topsoil from a nearby Pamunkey soil (Typic Hapludalfs; Soil Survey Staff, 2014a) were undercut to a 15-cm depth beforehand to prevent differences in the average plot elevation after topsoil placement (Dickinson, 2007). The topsoil treatments were applied on October 22, 2003. Compost treatments were applied volumetrically based on a measured volume/weight ratio and are given in units of wet weight applied and were applied on October 27, 2003. The compost amendment was 50.4% solids with a carbon to nitrogen ratio of 20.6, and total organic carbon content of 12.61% (Dickinson, 2007). All plots received the same fertilizer treatment of 280 kg ha^{-1} 10-10-10 (N - P_2O_5 - K_2O) fertilizer in October 2003. After topsoil and compost treatments were applied, the entire experimental area was chisel plowed to 15 cm on October 30, 2003. The topsoil amendment was dominantly loam Ap horizon removed from nearby gravel mined lands, although there was minor textural variation (Dickinson, 2007). In 2003, the surface soils were sampled by plot and particle size (0-3 cm) of plots in the treatments without topsoil contained 93-98% sand. The deeper (25 to 27 cm) samples taken in 2006 were all sand textured, with sand content ranging from 89-98%. A random sample of soil colors from nine plots including all treatments were described in 2003 (Table 2.1; W. Lee Daniels, pers. comm.).

Each experimental unit contains one shallow excavated pit, with an original diameter of approximately 0.75 m wide and 20 cm deep, and an adjacent 0.75 m diameter mound of soil excavated from the pit to simulate windthrow microtopography. Pits and mounds were installed in March, 2004. Also, in March, 2004, one bald cypress was planted in each pit, one on each mound, and one or more on level ground in each experimental unit (Dickinson, 2007; Pietrzykowski et al., 2015). A mix of second-year tubeling trees were planted on April 23-26, 2004 at an average density of 1,086 trees ha $^{-1}$ (Dickinson, 2007). Trees planted include willow oak (*Quercus phellos* L.), sycamore (*Platanus occidentalis* L) green ash (*Fraxinus pennsylvanica* Marsh.), hazel alder (*Alnus serrulata* [Ait.] Willd.), and bald cypress. An herbaceous seed mix was applied on May 10-14, 2004 to the entire experiment site after soil amendments were added. The seed mix contained spotted ladysthumb (*Polygonum persicaria* L.), Pennsylvannia smartweed (*Polygonum pensylvanicum* L.), arrowleaf tearthumb (*Polygonum sagittatum* L.), rice cutgrass (*Leersia oryzoides* L.), fringed sedge (*Carex crinita* Lam.), and redtop panicgrass (*Panicum rigidulum* Bosc ex Nees) (Dickinson, 2007).

By spring 2005, the hydrology of the site met the COE and VA DEQ criteria for wetland hydrology. This determination was confirmed by well readings that indicated the freshwater forested wetland was hydrologically-connected to the tidal cycle of the James River (Vanasse Hangen Brustlin, 2005), mainly through a cyclic pulse of groundwater through its very sandy substrate.

Sampling and Analysis

One detailed soil description to 30 cm (a mini-profile) was performed in a random location in each plot according to USDA standards (Schoeneberger et al., 2012) in 2005, 2007, and 2015. Soils in 2005 and 2007 were described by Mike Nester. Exclusions used for mini-profile location included being at least 30 cm away from plot edges, the base of trees to avoid dense roots, and any sites disturbed by macrofauna or previous-excavations. Soil colors were described and interpreted to the nearest half Munsell® color chip.

In 2006, samples were collected from 0-3 and 20-25 cm depths and analyzed for particle-size analysis by pipette method (Gee and Bauder, 1986). In 2015, one sample per depth or horizon was analyzed per experimental unit. Organic matter was removed from the surface horizon samples by adding H_2O_2 and applying heat (Burt, 2004). The samples were then analyzed using the hydrometer method (Gee and Bauder, 1986).

Soils in differing microtopographic positions (pit, mound) in every plot were sampled to approximately 15 cm using a 3.18 cm diameter push-probe. There was a total of 19 mound samples and 20 pit samples taken where bald cypress survived in 2015. These samples were analyzed for color value and chroma. One sample was taken in each microtopographic location to minimize disturbance.

For statistical analysis of treatment effects on measured parameters, data distributions were tested for normality (using a combination of graphical analysis and appropriate tests), overall one-way ANOVA was performed, and then Tukey's HSD test was utilized to contrast means if the overall ANOVA was significant. When parameter distributions were not normal, a Kruskal-Wallis nonparametric test was used (Kruskal and Wallis, 1952) followed by the Wilcoxon rank sum test to contrast treatments. Time comparison data were examined by paired t-tests ($\alpha = 0.05$). Delta values (e.g. 2015 value subtracted by 2006 value) were used to test if the differences in parameters (e.g. increase in OC) varied by treatment.

Delta values were then treated as dependent variables and tested using the methods above. The statistical software JMP (SAS, Cary, NC) was used, and $\alpha = 0.05$ for all statistical analysis.

Results

Amendment Effects

Soil colors measured in field for the upper 15 cm of selected plots in 2003 are listed in Table 2.1. In 2003, immediately after application of treatments, the soils had oxidized matrix colors with hue of 10YR, value 5-6, and chroma 3-8. There were common (5 to 10%) black to dark brown organic-stained zones in plots where compost had been incorporated.

In 2005, two years after compost, topsoil and tillage were applied, most plots in treatments 4 and 5 (topsoil plots) had developed only one ^Ap horizon in the loamy topsoil parent material. The underlying horizons were ^C, ^Cg, or 2^C horizons. However, two out of four plots in treatment 4 had more than one horizon in the topsoil (^AC horizon in plot 2, ^Cg1 in plot 4). All plots in treatment 5 had only an Ap horizon in the topsoil layer. There was no subangular blocky structure in any plot at the wetland in 2005; only weak granular structure in seven ^Ap horizons and one ^AC horizon. Five of the ^Ap horizons with weak granular structure were in one of the eight loamy topsoil treatment plots. Only two sandy surface plots had developed weak granular structure in the ^Ap horizon. About half of the plots (10 out of 21) had developed a ^Cg horizon with strong gleying. Overall, there was very little structure development in 2005, two years after wetland creation and treatment application.

By 2007, three plots had developed a B horizon (^Bg in plots 4 and 15, ^Bw in plot 2), all in loamy topsoil. B horizon formation was determined by development of weak structure (Bw), or by weak structure and a reduced matrix (Bg). Seven out of eight plots in topsoil treatments developed a second layer below the ^Ap. Horizon distinctions in sandy textured layers (treatments 1-3, and the lower horizons of treatments 4 and 5) were made on the basis of dominant gray color (^Cg indicating long-term saturation and water table height). All plots except two had a horizon with strong gleying (^Bg, ^Cg). Four years after treatment application, profile development was seen mostly in the plots with loamy soil added (treatments 4 and 5).

Average soil properties (n = 4 or 5) described in 2015 are reported by treatment (Table 2.2). In 2015, every soil had a thin (approximately 5 cm) ^Ap (A horizon) at the surface overlying a ^C, ^Cg, or 2^C (C horizon) within the 30-cm depth. Soils that formed in loamy topsoil (treatments 4 and 5) had either ^Bg or ^Bw (B horizon) below the ^Ap horizon. By 2015, all plots in treatments 4 and 5 had at least two horizons (^Ap and ^Bw and/or ^Bg) in the loamy parent material. Some loamy plots had two B horizons, labeled ^Bg1 over ^Bg2, or ^Bw over ^Bg. The B horizon structure was either weakly or moderately expressed in the loamy topsoil. All horizons in the loamy topsoil except one had developed weak or moderate soil structure. Every plot in treatments with loamy topsoil added (treatments 4 and 5) had one or more B horizons. All B horizons were either ^Bw or ^Bg; there were too few signs of clay translocation (e.g. clay films) for Bt horizons. One horizon in loamy topsoil was described as a structureless, massive Cg horizon. All horizons in the sand parent material (treatments 1-3 and the lower horizons of treatment 4 and 5) were either ^Ap, ^C, or ^Cg. The only structure development in sandy plots was in the surface horizon, not below. No B horizons had developed in the sandy textures due to lack of color difference and structure development. Most sandy ^Ap horizons had weak subangular blocky structure, but one plot had moderate granular structure. There were only two plots (20 and 21) that did not have a horizon with strong gleying (Bg or Cg horizon). Figure 2.3 shows an example of a soil plug from three different treatments (control, 156 Mg ha^{-1} compost, topsoil). Over 10 years, there was more horizon development in loamy horizons than in the sandy horizons.

Immediately after application of amendments in 2003, the soils in the wetland had oxidized matrix colors with hue of 10YR, value 5-6, and chroma 3-8 (Table 2.1). There were black to dark brown compost stained zones in plots that had compost applied (W. Lee Daniels, pers. comm.). The orange color of the sand indicated oxidized iron (Fe^{+3}) coatings on sand grains in 2003. Redox features were found in every plot by 2005, approximately one and a half years after amendments were added. This is similar to results by Stolt et al. (1998) who found redox features forming within two years on simulated peds amended with OM. There were more redox features (concentrations and depletions) present in A and C horizons in 2005 than in 2015.

From 2005 to 2015, average moist ^Ap horizon values decreased by Munsell® color 1.6 color units ($p<0.0001$), chroma decreased by 1.4 ($p<0.0001$), quantity of redox concentrations decreased by 12.5% ($p<0.0001$), and redox depletions decreased by 2.5% ($p=0.0057$) (Table 2.1). Over time, distinct ^Ap horizons formed in all plots by 2015. Figure 2.4 shows the progression of ^Ap horizon development in a control plot from 2005 to 2015. Figure 2.5 shows a comparison of a topsoil plot in treatment 1 in 2005 and 2015. The relative decreases in value, chroma, concentration content, and depletion content did not vary by treatment ($p=0.4776$, $p=0.3530$, $p=0.4928$, $p=0.3402$ respectively).

From 2005 to 2015, average moist C horizon values increased by 0.8 Munsell® color units ($p<0.0001$), chroma decreased by an average of 1.0 Munsell® color unit ($p<0.0001$), quantity of redox concentrations decreased by 1.4% ($p=0.0209$), and redox depletions decreased by 1.7% ($p=0.0283$). The increase in value and the decreases in chroma, depletions, concentrations did not vary by treatment ($p=0.8955$, $p=0.4440$, $p=0.6818$, $p=0.6687$). Overall, at 25-30 cm depth, soils developed higher value and low chroma colors, and the amount of redox concentrations and depletions decreased (Table 2.3). These changes resulted in more ^Cg and ^Bg horizons in 2015 than in 2005.

Colors in 2015 analyzed across ^Ap (A horizons) and ^C, ^Cg, 2^C, or 2^Cg (C horizons) (Table 2.3) revealed that topsoil treatments had a higher A horizon value than the control treatment ($p=0.020$), indicating that the finer particle-sized topsoil was not darkened by carbon to the same extent as the sandy surface soils. The higher OC content of Ap horizons resulted in a much lower mean value ($p < 0.0001$) than C horizons. Redox depletions and concentrations were not found in Ap horizons of sandy soils, but 0.5% concentrations were found in the loamy topsoil Ap horizons. Redox depletions ($p=0.2103$) and concentrations (p=0.7725) did not vary by treatment in C horizons. The mean amount of concentrations depletions visibly appeared to vary by treatment, but differences were difficult to determine statistically because of unequal variances and small sample sizes.

In 2005, 2 years after excavation and treatment application, none of the plots at WWE met a HSFI. Descriptions made in 2005 described redox feature content in qualitative terms (i.e. few, common, many) instead of percent estimates. Plot 5 in treatment 1 (control) met indicator S6 if the concentration content was $\geq$ 10%, which was described as "common" (2 to 20%). No other plots in 2005 met a HSFI (USDA-NRCS, 2017; Table 2.4). In 2007, nine out of 13 sandy plots met one or more HSFI's (S5, S6), and five out of eight loamy plots met an HSFI (F3). From 2007 to 2015, the amount of sandy HSFI's decreased from nine to four, and the number of loamy indicators increased from five to eight. The five plots that previously met S5 but met no HSFI in 2015 indicate that the sand became less gray (chroma increased) during that time. Loamy soils in treatments 4 and 5 became more gray (chroma decreased) over time and met more HSFI's in 2015 than in 2007 or 2005.

Statistical tests were not used to determine soil textural differences over time (Table 2.5). A horizon silt content increased in treatments 1, 2, and 3 from 2005 to 2015 (p<0.0001, 0<0.0001, p=0.0003 respectively). An increase in surface horizon silt content was not detected in treatments 4 and 5 (p=0.9050, 0.9957). Silt content of C horizons increased over time in treatments 1 through 4 (p=0.0145, p=0.0057, p=0.0006, p=0.0023), and there was a trend of increased silt in treatment 5 (p=0.0764). In treatments without topsoil added, there was an increase in silt content in ^Ap and C horizons.

Microtopographic Effects

All mineral soil surface layers in pits and mounds were described as ^Ap horizons (Table 2.6). ^A horizons from microtopography locations had an average depth of 5.1 cm. Second horizons on mounds were estimated to be either ^Bg or ^Bw horizons (some loamy plots) or ^C or ^Cg horizons (loamy and sandy plots) but that could not be confirmed because we did not dig pits to describe them. Soil pits had significantly lower value ($p<0.0001$) and chroma ($p=0.0147$) than mounds in their surface horizons, and lower chroma than mounds and level plots in the second horizons ($p<0.0001$).

Discussion

Some soils in loamy topsoil treatment plots developed readily observable redox features and ^Bg horizons in about four years after construction. By 12 years after construction and treatment application, all loamy soils had at least one B horizon. Horizon development occurred faster in the loamy topsoil due to the higher clay content that led to redox feature formation and structure development. In sandy horizons (treatments 1-3, lower horizons of treatments 4 and 5), horizons were distinguished largely based on color in 2005, 2007, and 2015. Even in 2015, 12 years after treatment applications, there was no significant soil structure formation in sandy layers except in ^Ap horizons. ^Cg horizons occurred at varying depths across the wetland, and with greater frequency in years 2007 and 2015 than in 2005. Most plots (19 out of 20) had a horizon with a strongly gleyed matrix within 30 cm in 2007 and 2015, while only 10 out of 20 did in 2005. The two plots (20 and 21) that did not have any horizons with strong gleying (^Bg or ^Cg horizon) in 2015 had one Cg horizon in 2006. Mini-pits were dug in locations not previously sampled, so it is possible that there was variation within those plots (i.e. strong gleying might not occur uniformly across the plot). These two plots that did not have any horizons with strong gleying in 2015 were located on the drier side of the wetland towards the road (Figure 2.2), therefore they may have had more aerobic conditions than the other plots. The slight wetness gradient was visually observed but not measured. Plots near plot 21 (front right corner of the wetland) were drier than plots near plot 1 (back left of the wetland). The OM that was originally added in 2003 was decomposed over time into humus and dissolved OC, some of which eluviated into the subsoils and drove the microbial reduction. Plant roots also likely contributed to subsoil OC. So, the subsoil OC led to Fe^{+3} to Fe^{+2}. Clay in the loamy topsoil treatments helped develop subsoil structure development in those plots. The lack of clay has led to a slow subsoil structural development in sandy plots. The sandy plots did develop granular soil structure in ^Ap horizons by 2015 due to high OC content, but no moderately structured B horizons were formed.

All color parameters changed from 2005 to 2015, but none of the delta values varied by treatment. Across the wetland site, ^Ap horizons became darker over time, C horizons developed higher values and lower chroma colors, and redoximorphic concentrations and depletions decreased in both horizons. Over 12 years, value and chroma decreased (became darker) in the ^Ap horizons as the originally applied compost decomposed into humus, and as local plant litter, roots, and deposited OM accumulated and decomposed into humus. Chroma likely decreased (became less intense and more gray) due to OM additions as well as reduction of oxidized Fe. ^Ap horizons became uniformly darker over time, as the decreases in ^Ap horizon value and chroma did not vary by treatment (i.e., compost and topsoil did not lead to faster ^Ap horizon color development than the control). Surface soil colors likely decreased in value due to an increase of OC over the same time period (Figure 2.4), and prolonged saturation. The decrease in moist Ap horizon chroma was likely due to Fe reduction and C accumulation between 2005 and 2015. Redox formed within about one and a half years at this wetland (2005) and remained in plots in 2007.

In ^C horizons, chroma decreased after extended periods of saturation and reduction of Fe. Soil colors overall became darker and more gray than the original 10YR 5/3 to 10YR 6/8 colors. Accumulating OM was dispersed over a larger surface area in the loam topsoil treatments and did not darken the soil as much as in the sands. The observed color change (value and chroma decrease in ^Ap horizons; value increase and chroma decrease in C horizons) did not vary by treatment, so the change in soil colors over time was not due to compost or topsoil amendments.

By 2015, twelve of the 21 plot descriptions met NTCHS HSFI's. Although the topsoil plots (treatments 4 and 5) did not have surface soil colors as dark as the other treatments, all topsoil plots met

HSFI F3 - Depleted Matrix, while only three of the sandy surface plots met HSFI S5 - Sandy Redox in 2015. The C horizon colors, rounded to the nearest integer, all met the color requirement for depleted matrix (value 4 or more with chroma 2 or less). However, the F3 - Depleted Matrix is not recognized in sandy particle sizes, and the similar S5- Sandy Redox indicator requires redox concentrations of at least 2% that many plots did not have. Sands dredged from river bottoms may have had very little Fe that can be reduced and later concentrated as soft masses; however, at this experimental site, photos and soil descriptions show that the sands were brownish orange in color, proving that the sand grains had light Fe-oxide coatings. Some of the Fe may have been reduced and moved out of the soils over time after the site was excavated. The sandy plots may have met more HSFI's in 2007 than in 2015 due to the "fresh" quality of the newly added compost; by 2015, microorganisms had decomposed much of the original compost, and had less of an easily decomposable food source. It is uncertain whether more of the sandy soils will meet HSFIs over time, except for HSFIs related to organic matter accumulation or redistribution (e.g., A7 Mucky Mineral; A11 Depleted Below Dark Surface). At WWE it took about 1.5-4 years to form HSFI's, which is slightly faster than results by Vepraskas et al. (1999) who found the F3- Depleted Matrix indicator formed in 4-5 years.

Topsoil treatments helped maintain more HSFIs over time compared to the sandy control. Soil scientists, contractors, delineators, engineers, and regulators may want to consider that hydric soils can form relatively quickly in sand and finer particle sized soils in created wetlands, as long as the soils are not continuously disturbed and have the proper conditions for Fe reduction and oxidation and/or OC accumulation. The absence of HSFIs in sandy or loamy created wetlands that are tidally and frequently flooded is not likely to be due to insufficient time for formation alone. Soils that are low in OC and/or Fe or form in problem parent materials may take longer to develop HIS. At this study site, the floodwater and tides from the James River contained a source of OM and possibly dissolved OC and Fe. It is likely that the combination of daily tidally driven saturation at or near the surface in these soils along with natural litterfall and flooding inputs of C masked any expected positive effects of the compost additions. This may have also been due to the relatively low compost application rates employed. These results are consistent with literature reporting that sandy soils may have difficulty in developing redoximorphic features to meet HSFIs (Kuehl et al., 1997; Robinette et al., 2004; Rossi and Rabenhorst, 2015).

^Ap horizons in treatments 1 through 3 (sandy soil) and ^C horizons in treatments 1 through 4 increased in clay and silt content over time. Silt may be brought into the wetland on periodic tidal influxes and storm flooding events, which would explain increased silt content in Ap horizons. An increase in silt content from 2005 to 2015 is evidence that the site is serving the wetland function of sediment trapping. And increase in silt content of C horizons is likely due to eluviation of silt into the subsoil.

There are overall few lasting effects of compost on soil morphology. A lack of long-term compost treatment effect is likely related to several factors: a loose, low BD site; ideal hydrology; low compost loading rates; organic additions from tides and established vegetation. The site was carefully constructed to minimize vehicle traffic and compaction, which is in contrast to many wetlands that are compacted during creation (Bishel-Machung et al., 1996; Whittecar and Daniels, 1999; Campbell et al., 2002). Also, the wetland site was created in loose sandy dredge which is more resistant to compaction than finer textures (Brady and Weil, 2017). The hydrology at this site fluctuates daily and includes saturation within 15 cm of the soil surface most days of the year. The site is also impacted by tidal surface water that likely deposits OM, in addition to the OM deposits from the established vegetation at the site.

Conclusions

Over the 12 years since construction and treatment application, soil morphological properties in this created wetland progressed towards natural wetland soil properties (low value and low chroma Ap horizons, strong gleying in the subsoil, HSFIs, silt increase in surface soils by sediment trapping). Redox features formed within two years at this site, and HSFI’s formed within four years. There were more redox concentrations present in 2005 than in 2015 across the wetland. The loamy soil amendments retained more redoximorphic features after 12 years than the sandy soil treatments. The addition of fine textured topsoil to the original sandy soils led to faster soil structure development and more stable HSFI's. It is possible that changes in soil properties over time due to compost treatment would have been noted if higher rates were used (>156 Mg ha^{-1}) or the hydrologic regime was less ideal. At the rates used (78 Mg ha^{-1}, 156 Mg ha^{-1} compost), there seem to be few lasting effects of compost on soil morphology after 12 years in this unique created wetland. Soil scientists, contractors, delineators, engineers, and regulators may want to consider the length of impact of OM amendments for very wet created wetlands. If the purpose of the organic amendment in frequently and tidally flooded sandy wetland soils is to replicate natural wetland soil conditions to enhance vegetative establishment, provide nutrients, and lower bulk density, it is may be a valuable addition. However, other creation factors (e.g. hydrology, compaction) may be equally, if not more important than OM loading rate in the long-term on tidal freshwater sites such as this one.

The addition of microtopography (creation of pits) is a valuable strategy for increasing the variety of plant and animal habitats and soil conditions within created wetland soil landscapes. Adding microtopography is recommended for tidally-influenced and flooded created wetlands regardless of surface texture.

We recommend adding OM to sandy created wetland soils if the initial OM, OC, BD, or hydrology are limiting. However, in this sandy wetland with nearly ideal hydrology and non-limiting BD, compost amendment at these rates (78 and 156 Mg ha^{-1}) had little to no effect in the long-term. Future research is needed to test the long-term impact of adding amendments to sandy created wetlands with drier and/or less consistent hydrology.

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Tables and Figures

Table 2.1. Moist Munsell® soil colors of selected plots in the upper 15 cm immediately after treatment applications in October 2003 (W. Lee Daniels, pers. comm.).

Plot	Treatment	Moist Munsell® Colors
17	1 (fertilized control)	10YR 5/4 with many redder individual Fe-coated grains
20	1 (fertilized control)	10YR 5/3.5 with common redder individual Fe-coated grains
16	2 (78 Mg ha^{-1} compost)	10YR 5/3.5, with many redder individual Fe-coated grains and common black (7.5YR 2/0) compost stained masses
3	2 (78 Mg ha^{-1} compost)	10YR 5/4, 5% black compost stained masses
1	3 (156 Mg ha^{-1} compost)	10YR 5/6 and 6/3, 10% black stained compost masses
15	4 (topsoil + 78 Mg ha^{-1} compost)	90% 10YR 5/4 and 5/8, with 10% 10YR 5/2.5 compost stained masses
18	4 (topsoil + 78 Mg ha^{-1} compost)	90% variegated 10YR 5/4, 10 TR 6/8, and10YR 6/3, with common (10%) black compost stained masses
19	5 (topsoil only)	Variegated 90% 10YR 6/8 and 10% 10YR 6/3

Table 2.2. Average properties of similar horizons (n = 4 or 5 for controls) in each treatment as described in 2015.

Horizon	Depth	Structure Grade	Structure Shape	Texture	Matrix color Hue value/chroma	Redoximorphic Features Conc.	Redoximorphic Features Depl.
	cm					%	%
Treatment 1: Control							
^Ap	4.4	weak	subangular blocky	Loamy fine sand	10YR 2.2/1.4	0	0
^C	19.3	structureless	single grain	Sand	10YR 5.3/3.0	12.8	7.5
^Cg	30+	structureless	single grain	Sand	10YR 5.3/1.4	7	0.3
Treatment 2: 78 Mg ha^{-1} compost							
^Ap	5.5	weak	subangular blocky	Loamy fine sand	10YR 2.3/2.3	0	0
^C	23.3	structureless	single grain	Sand	10YR 5.3/3.0	11.8	2.3
^Cg	30+	structureless	single grain	Sand	2.5Y 5.0/1.8	5.5	0.3
Treatment 3: 156 Mg ha^{-1} compost							
^Ap	5.8	weak	subangular blocky	Loamy fine sand	10YR 2.3/1.8	0	0
^C	23	structureless	single grain	Sand	2.5Y or 10YR 5.0/3.0	11.3	3.7
^Cg	30+	structureless	single grain	Sand	2.5Y 5.2/1.6	16.6	1.2
Treatment 4: 15 cm topsoil plus 78 Mg ha^{-1} compost							
^Ap	4.3	weak or moderate	granular	Clay loam	10YR 3.0/2.3	0.5	0
^Bg	20.3	weak	subangular blocky	Clay loam	10YR 4.7/2.0	12.5	4.8
2^Cg	30+	structureless	single grain	Sand	2.5Y 5.9/1.7	9.7	10.7
Treatment 5: 15 cm topsoil only							
^Ap	3.7	moderate	granular	Sandy clay loam	10YR 3.0/2.8	0.5	0
^Bg	13.3	weak or moderate	subangular blocky	Clay loam	2.5Y 5.0/2.0	14.8	7.3
^Bg2 or ^Cg	20.7	weak or structureless	subangular blocky or single grain	Clay loam	10YR 5.0/2.0	8.7	5
2^Cg	30+	structureless	single grain	Sand	10YR 4.5/1.5	13	2.8

Table 2.3. Soil color change in surface soil and subsoil from 2005 to 2015. Delta values are means from paired t-tests by horizon.

	Value			Chroma			Concentrations			Depletions		
								%			%	
Treatment*	2005	2015	Δ Value	2005	2015	Δ Chroma	2005	2015	Δ Conc.	2005	2015	Δ Depl.
------- Surface soil (approximately 0-5 cm) -------												
1- Control	4.0	2.2b	-1.8	3.0	1.4	-1.6	11.0	0.0	-11.0	0.6	0.0	-0.6
2- C78	4.0	2.3ab	-1.8	3.0	2.3	-0.8	14.0	0.0	-14.0	3.3	0.0	-3.3
3- C156	4.0	2.3ab	-1.8	3.3	1.8	-1.5	10.5	0.0	-10.5	0.3	0.0	-0.3
4- TS+ C78	4.4	3.3a	-1.1	3.8	2.2	-1.6	11.6	0.0	-11.6	4.8	0.0	-4.8
5- TS	4.5	3.0a	-1.5	4.0	2.8	-1.3	16.0	0.0	-16.0	3.3	0.0	-3.3
------- Subsoil (approximately 25-30 cm) -------												
1- Control	4.2	5.2	1.0	2.8	2.2	-0.7	2.2	0.1	-2.0	1.8	0.4	-1.4
2- C78	4.0	4.8	0.8	3.0	1.8	-1.5	2.4	0.0	-2.4	0.2	0.0	-0.2
3- C156	4.0	4.8	0.8	3.6	2.0	-1.6	2.2	0.1	-2.1	4.4	0.0	-4.4
4- TS+ C78	4.4	5.1	0.7	2.6	2.1	-0.5	0.4	0.1	-0.3	4.4	1.5	-2.9
5- TS	4.0	4.7	0.7	2.8	1.8	-1.0	0.5	0.1	-0.4	0.3	0.2	-0.1

* Treatment symbols: C78 = compost at 78 Mg ha^{-1}; C156 = compost at 156 Mg ha^{-1}; TS+C78 = topsoil plus 78 Mg ha^{-1} compost; TS = topsoil only.

Table 2.4. Treatments and plots and their Hydric Soil Indicator Status in 2005, 2007, and 2015 (USDA, NRCS 2017). Table cells that are blank did not meet a hydric soil indicator. Indicators used are: A11 - Depleted Below Dark Surface; S5- Sandy Redox; S6- Stripped Matrix; and F3- Depleted Matrix.

Treatment	Plot	Hydric Soil Indicator		
		2005	2007	2015
1- Control	5	S6*	S5, S6	
	7		S5, S6	
	9			S5, A11
	17			S5
	20		S5	
2- 78 Mg ha^{-1} Compost	3		S6	
	11		S5	
	14		S5	
	16			S5
3- 156 Mg ha^{-1} Compost	1		S5, S6	
	6		S6	S6
	10		S5	
	21			
4- Topsoil + 78 Mg ha^{-1} Compost	2			F3
	12		F3	F3
	15		F3	F3
	18			F3, A11
5- Topsoil	4		F3	F3, A11
	8		F3	F3
	13		F3	F3
	19			F3

*Depletion percent described as “common”, which is defined as 2 to 20%. HSFI S6 requires $\geq$ 10% depletions.

Table 2.5. Mean soil textures in surface Ap horizons (0-5 cm) and subsoil C horizons (25-30 cm) in 2006 and 2015 (n=5 for treatment 1, n=4 for treatments 2-5).

		---------------- 2006 ----------------				---------------- 2015----------------			
Treatment*	Depth	Sand	Silt	Clay	Texture Class	Sand	Silt	Clay	Texture Class
	cm	------- % -------				------- % -------			
1- Control	0-5	95.9	0.2	3.9	Sand	84.4	7.3	8.2	Loamy Sand
	25-30	97.4	0.9	1.8	Sand	94.9	3.0	2.0	Sand
2- C78	0-5	95.4	0.3	4.3	Sand	82.0	7.6	10.4	Loamy Sand
	25-30	97.5	0.4	2.1	Sand	94.6	2.7	2.7	Sand
3- C156	0-5	96.6	0.2	3.2	Sand	80.7	9.7	9.6	Loamy Sand
	25-30	96.2	0.3	3.6	Sand	94.9	2.8	2.3	Sand
4- TS+C78	0-5	52.8	27.2	20.1	Sandy Clay Loam	36.9	28.2	34.9	Clay Loam
	25-30	96.3	0.2	3.5	Sand	94.8	2.6	2.5	Sand
5- TS	0-5	42.2	35.0	22.8	Loam	50.0	23.9	26.1	Sandy Clay Loam
	25-30	94.8	1.0	4.2	Sand	94.6	2.6	2.8	Sand

* Treatment symbols: C78 = compost at 78 Mg ha^{-1}; C156 = compost at 156 Mg ha^{-1}; TS+C78 = topsoil plus 78 Mg ha^{-1} compost; TS = topsoil only.

Table 6. Average moist Munsell® color in surface and 2nd horizons

	Surface		2nd Horizon	
Location	Value	Chroma	Value	Chroma
Mound	3.2a	2.3a	4.7a	3.1a
Pit	2.4b	1.9b	4.5a	2.1b

* Within columns, significant differences are denoted by differing letters (α= 0.05 significance level).

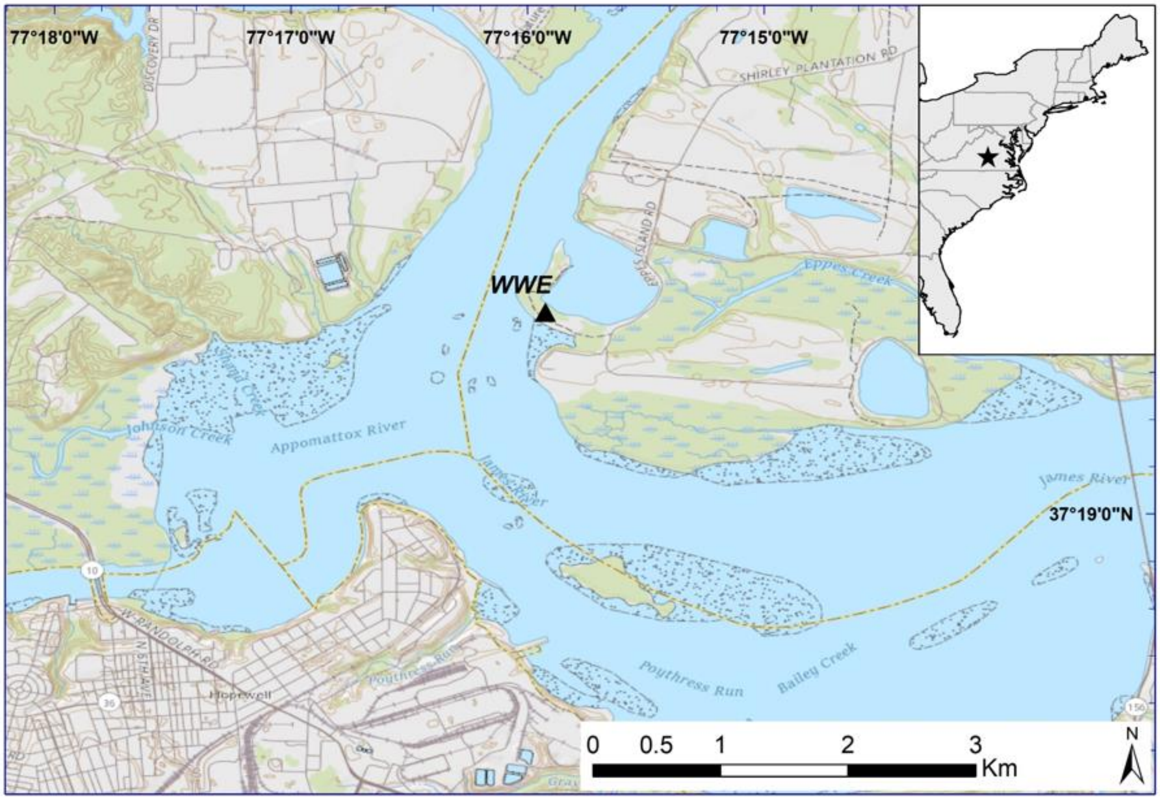

Figure 2.1. Location of the Weanack Wetland Experiment (WWE) in Charles City County, Virginia (credit: Patricia Donovan, Virginia Tech).

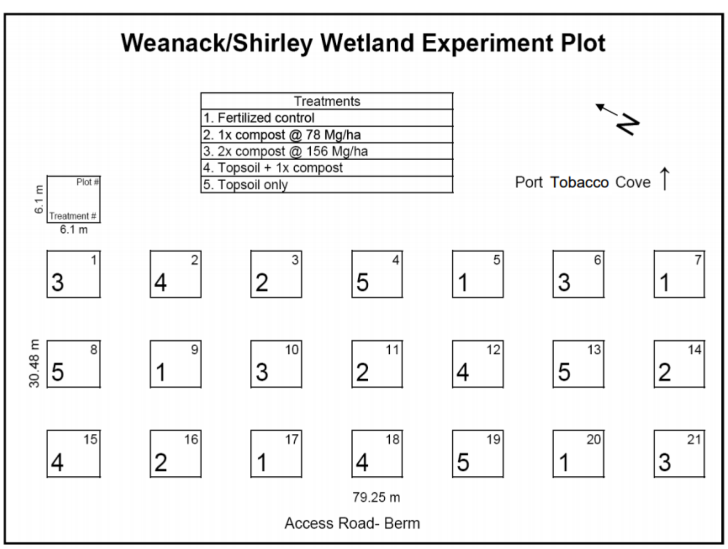

Figure 2.2. The Weanack Wetland Experiment site showing the plot and treatment layout.

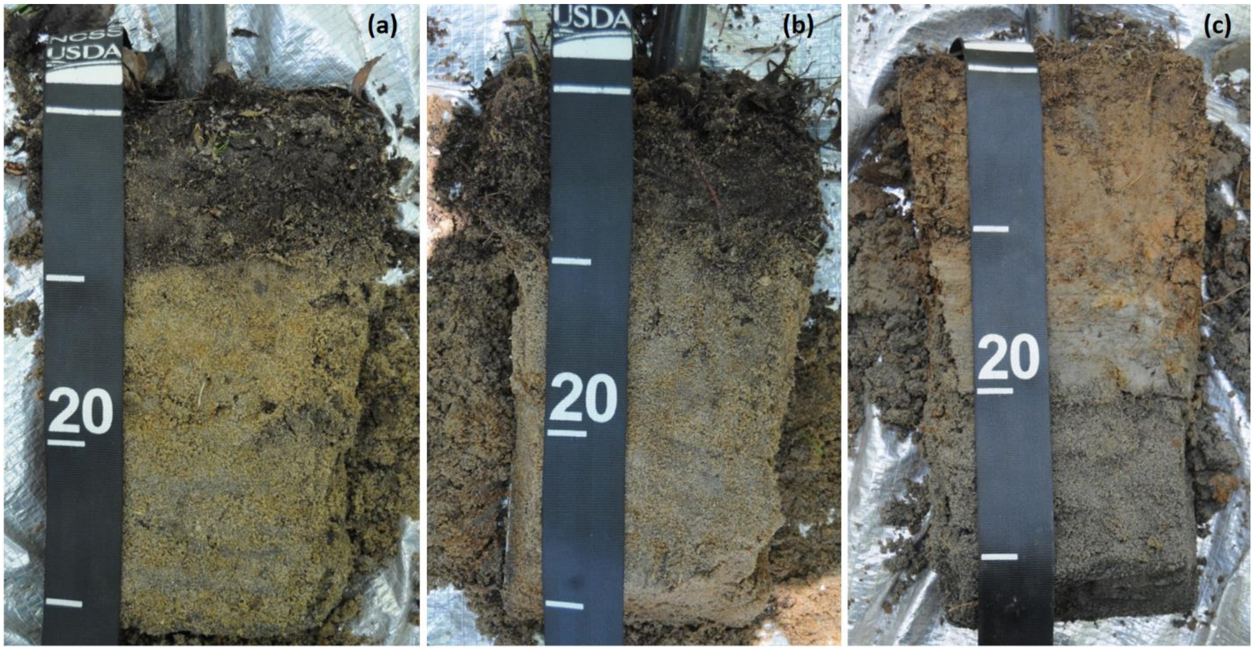

Figure 2.3. Soil plugs taken in 2015. From left to right: a) Plot 5, the control treatment; b) Plot 21, 156 Mg ha^{-1} of compost applied in 2003; c) Plot 19, loamy topsoil applied in 2003. The contact between the loamy topsoil and sand is at 20 cm. (Photos by Emily Ott)

Figure 2.4. Sandy soil profiles at WWE over time. (a) Sandy upland dredge in 2003 before excavation (photo by Lee Daniels). Original sand was approximately 6-m deep. (b) Soil plug taken from plot 5, treatment 1 (control) in 2005 (photo by Mike Nester). (c) Soil plug taken from plot 5 in 2015 (photo by Emily Ott).

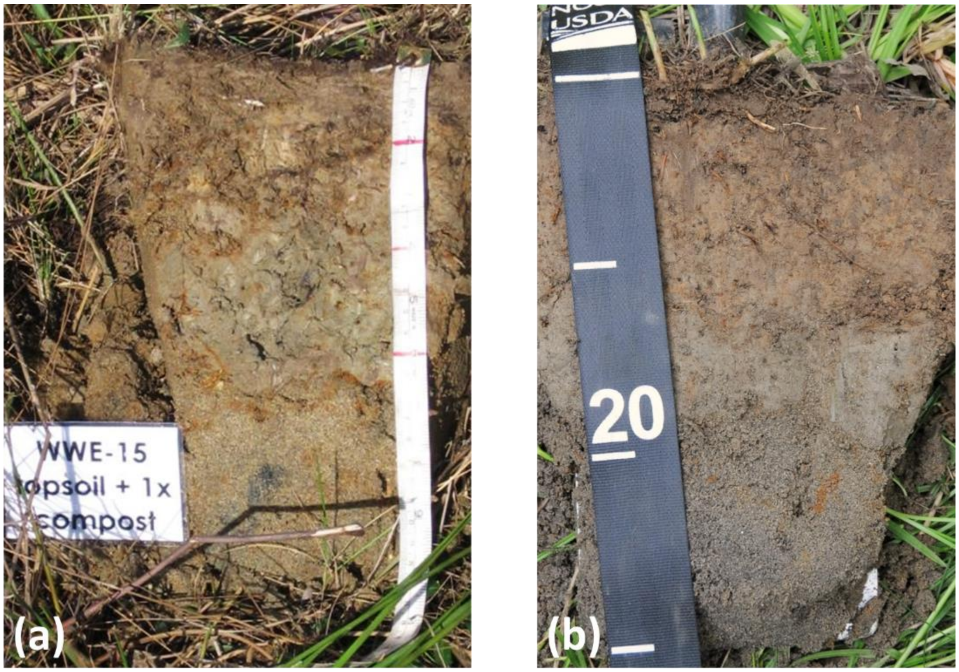

Figure 2.5. Loamy soil profiles over time at WWE. (a) Soil plug taken from plot 15, treatment 4 (topsoil plus 78 Mg ha-1 compost) in 2005 (photo by Mike Nester). (b) Soil plug taken from plot 15 in 2015 (photo by Emily Ott).

3. Amendment and Microtopography Effects on Bulk Density and Chemical Properties in Created Tidal Sandy Freshwater Wetland Soils

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Abbreviations: BD: bulk density; OC: organic carbon; OM: organic matter; TC: total carbon; TN: total nitrogen

Abstract

Created wetlands used to mitigate negative impacts to natural wetlands often have lower organic carbon (OC) and higher bulk density (BD) than natural wetlands. Organic matter (OM) amendments may improve soil properties soon after construction and treatment application, but long-term effects and soil properties are seldom studied. This study describes the changes over time of BD, OC, total carbon (TC) total nitrogen (TN), soil mass carbon (C), and plant available nutrients in the upper 30-cm of a sandy freshwater tidal created wetland in the Coastal Plain of Virginia. After construction in 2003, five treatments were applied (78 Mg ha^{-1} compost-wet, 156 Mg ha^{-1} compost-wet, 15 cm loamy topsoil plus 78 Mg ha^{-1} compost, 15 cm loamy topsoil without compost, and control). Soil samples for physical and chemical analysis were taken in 2006 and 2015. We measured BD, TC, TN, and mass soil C by treatment, and BD, TC, and TN by microtopographic positions (pit, mound). Long-term treatment effects of loamy topsoil additions included a slow increase in some plant available nutrients (Ca and Mg) and higher ^Ap horizon BD (1.03 g cm^{-3}) than sandy (0.76 g cm^{-3}) treatments but no other long-term effects. We found no difference in BD or C-sequestration due to adding compost compared to the control treatment. In microtopography treatments, pits had higher TC (3.73%) as well as lower BD (0.87 g cm^{-3}) than mounds or level positions. We found no advantage for increasing mass soil C over time from adding compost or topsoil in this tidal freshwater setting. We recommend adding pit and mound microtopography to created wetlands for increasing diversity of habitat. Further study is needed to see if topsoil amendments are needed to improve revegetation success in sandy created wetlands in other Coastal Plain wetland types.

Keywords: hydric soil, compost amendment, topsoil addition, soil carbon

Introduction

Wetland creation (along with restoration and amelioration) is a technique used to offset net losses of wetlands and their functions impacted by development, road building, and agricultural land uses (Mitsch, 1992; Atkinson et al., 1993; Allen and Feddema, 1996; Brown and Lant, 1999). The most difficult type of wetland mitigation to successfully accomplish is the creation of wetlands from upland areas. Created wetlands frequently have not provided the same levels of essential ecosystem services of natural wetlands due to issues such as low organic or total carbon (TC) (Bishel-Machung et al., 1996; Whittecar and Daniels, 1999; Stolt et al., 2000; Fajardo, 2006), compaction (Bishel-Machung et al., 1996; Campbell et al., 2002), and limited rooting volume (Daniels et al., 2005). In addition, studies in wetlands have shown that organic matter (OM) additions are correlated with lower bulk density (BD) (Bishel-Machung et al., 1996; Collins et al., 1997; Bruland et al., 2009), but additional research is needed that determines appropriate rates of OM treatments, and the changes in soil properties of created wetland soils over time.

Soil OM accumulation in surface horizons and organic carbon (OC) distribution throughout the soil profile is slower in early years of created wetland development than in natural wetlands. This is because younger wetlands do not have the overall plant community root and litter inputs that are the source of OM accumulations and soil carbon (Ballantine and Schneider, 2009). Some research has been performed using models to predict the amount of time needed for created wetlands to approach properties similar to natural wetlands. Hossler and Bouchard (2010) reported that it may take as long as 300 years for soil in a newly created depressional, palustrine wetland to accumulate the same C in the upper 0-5 cm as a natural wetland. They examined five created wetlands that were three to eight years old, and four natural wetlands. The created wetlands were found to generally have fewer macroaggregates, less sand, more silt and clay, and higher BD. The time to equivalence for BD was estimated to be 70 years, and for OC was 400 years. Soil OC was positively correlated with macroaggregates and negatively correlated with microaggregates, silt and clay content, and BD. Overall, soil OC was lower in the created wetlands than in the natural wetlands. Wolf et al. (2011) found that non-tidal freshwater created wetlands 3-4 years old had lower gravimetric moisture, OC, TN, and higher BD than created wetlands that were 7-10 years old. Younger wetlands had had fewer growing seasons during which plant litter can be deposited by existing vegetation or surface flow events, and had had fewer cycles of root exudates, growth, and mortality.

Many studies have shown that adding OM during wetland construction improves wetland soil properties within the first few years. OM amendments may include leaf and lawn compost, food processing waste, and forest products (Stauffer and Brooks, 1997). Positive effects of OM additions include an increased phosphorous sorption index and lower BD (Stauffer and Brooks, 1997; Bruland and Richardson, 2004). However, in constructed wetlands, especially those that become aerobic for long periods, OM amendments may be oxidized and decomposed rapidly, so the positive effects may diminish over time.

Carbon sequestration is an important wetland function. In wetland ecosystems, the nonliving OC storage is often higher than in other ecosystems and provides an energy reserve for the ecosystem (Wetzel, 1992; Collins and Kuehl, 2001). Because created wetlands are developed to mitigate wetland loss or damage to natural wetlands, it is presumed that created wetlands should also serve as C sinks. However, compared to nearby or comparative natural wetlands, created wetlands often have low OC (Bishel-Machung et al., 1996; Whittecar and Daniels, 1999; Stolt et al., 2000; Fajardo, 2006). Fajardo (2006) evaluated 10 mitigation wetlands in Virginia, all of which were less than five years old at the time of sampling. Eight out of the 10 wetlands had surface (0-15 cm) soil TC less than 2%, despite most of the sites receiving OM amendment or topsoil return strategies. The low C content in the surface soils of the wetlands may have been due to the young age of the sites when sampled. Limited organic C (OC) research is available for created wetlands that are greater than 10 years old. Craft et al. (1988) reported that it may take some created marsh wetlands 15-30 years or more to develop total nitrogen (TN) and soil OC pools equivalent to that of natural wetlands. In their study, which included three organic soils and two mineral soils, soil nutrient pools increased with increasing marsh age and duration of saturated hydroperiod (Craft et al., 1998; Hackney and de la Cruz, 1982).

Wetlands that receive 15 cm of topsoil amendments during creation have higher mean soil moisture, OM, and phosphorous sorption index than created wetlands without topsoil amendments (Bruland and Richardson, 2004). Topsoil and OM, or topsoil alone may improve soil properties in wetlands created by excavation into subsoils with high BD or low OC (Bruland and Richardson, 2004). Particularly, topsoil amendments from donor wetlands may contain a wetland seed-bank and lead to increased vegetation diversity, number of species over time, invasive plants, canopy coverage, and biomass (Burke, 1997; McKinstry and Anderson, 2005). Topsoil salvaged from a natural marsh wetland increases soil nutrients, such as higher nitrate-N (Stauffer and Brooks, 1997).

Seasonally-saturated wetlands and forests commonly contain small or large irregular changes in a soil surface (i.e. pits and mounds) called microtopography that may develop from sediment accumulation, erosion, tree fall, or animal activity (Bruland and Richardson, 2005). In wetland soils, microtopography that results from tree fall creates pits that contain shallow water for longer than the rest of the surface, and mounds that are aerobic and slightly above the water table. This presence of anaerobic and aerobic zones can increase plant and animal diversity by increasing the number of plant species that can survive in the wetland (Titus, 1990; Vivian-Smith, 1997; Roy et al., 1999; Bruland and Richardson, 2005; Pennington and Walters, 2006). The inclusion of aerobic and anaerobic zones in wetlands affects biogeochemical cycling of nutrients, including N fixation, and Fe- and Al transformations and adsorption (Reddy et al., 1984; Darke and Walbridge, 2000). Microtopography also creates heterogeneous properties such as nutrient content, pH, and soil moisture (Beatty 1984; Paratley and Fahey, 1986; Bledsoe and Shear 2000).

Constructed wetlands typically do not contain microtopography due to extensive grading, construction design to specific soil or water table depths, and absence of large trees that fall during windthrow events (Stolt et al., 2000; Daniels and Whittecar, 2004). Therefore, adding microtopography should speed the time required for created wetlands to gain as many functions of less disturbed wetlands as possible.

Overall, previous research suggests that topsoil and OM amendments help created and restored wetlands reach the properties of natural wetlands in less time than when no amendments are used during wetland creation and soil reconstruction. The objectives of this study were to report changes in soil properties (BD, OC, mass C, TN, plant-available nutrient content) between 2005 and 2015 in a created wetland. Additional objectives were to analyze any increases or decrease in soil parameters over time by treatment to determine whether any treatments affected development of hydric soil characteristics over 12 years.

Materials and Methods

Site Description

The Weanack Wetland Mitigation Site is an off-site compensation created wetland located in Charles City County, Virginia, at 37.330922N, 77.265518W (Figure 3.1). The 2.74 ha mitigation wetland includes an emergent, shrub-scrub, and forested wetland. The wetland is on the James River floodplain in the Virginia Coastal Plain. The Weanack Wetland Experiment (WWE) is 0.24 ha located within the forested wetland, and comprises 21 experimental units that are each 6.1 m by 6.1 m.

Prior to wetland construction and application of soil amendments, the site was an approximately 6-m thick deposit of James River dredged sand (human-transported materials) (Figure 3.1). The dredge materials were placed in the 1950’s-70’s by the U.S. Army Corps of Engineers (COE), and was about 95% medium sand with Fe-coatings. This dredge material overlaid native hydric soils and shallow open water.

The pre-treatment (2003) soil formed in the sandy dredge material was excessively drained and was similar to the Lakeland soil series (Thermic, coated family of Typic Quartzipsamments). After excavation, the soil became poorly drained. The soil is in a series not designated but is estimated to be a member of the dredgic, acid, thermic family of Anthroportic Psammaquents, and is closest to the Osier series (siliceous, thermic family of Typic Psammaquents) (Soil Survey Staff, 2014b; John M. Galbraith, pers. comm.). The soils are human-transported materials, so after treatments were applied the soils were described as ^Ap over ^C, or ^Ap over 2^C in topsoil treatment plots. By 2015, ^Bw and ^Bg horizons also developed in the topsoil treatments. Soil horizons are referred to as Ap, B, and C for simplicity.

The site was partially excavated down to a seasonal high tide and graded in late 2003 and is now approximately 1.01 to 1.13 m above mean low tide. The experiment site is inundated during the non-growing season and large storms, but water is rarely above the surface during the growing season. Well readings from 2005 confirmed that the wetland is a tidal freshwater swamp that is hydrologically connected to the James River (Vanasse Hangen Brustlin, 2005). The well readings also confirmed that the site met COE and Virginia Department of Environmental Quality requirements for jurisdictional wetland hydrology (Vanasse Hangen Brustlin, 2005).

The experiment contains four treatments with four replicates each, and the control, which had five replications (treatment 1 = control, treatment 2 = 78 Mg ha^{-1} compost, treatment 3 = 156 Mg ha^{-1} compost, treatment 4 = topsoil plus 78 Mg ha^{-1} compost, treatment 5 = topsoil only). Plots in treatments 4 and 5 were undercut by 15 cm, and then received 15 cm of stockpiled Pamunkey (Typic Hapludalfs) soil on October 22, 2003 (Dickinson, 2007; Soil Survey Staff, 2014a). The topsoil applied was dominantly a loamy Ap, with some textural variation (Dickinson, 2007). Compost treatments were applied on October 27, 2003 volumetrically based on a measured volume/weight ratio and are given in units of wet weight applied. Chemical and physical analysis of the compost when applied showed it was composed of 50.4% solids, with OC content of 12.61%, and C:N of 20.6 (Dickinson, 2007). The plots (experimental units) were arranged as a completely randomized design. All plots received a fertilizer treatment of 280 kg ha^{-1} 10-10-10 (N - P_2O_5 - K_2O) fertilizer in October 2003. The experiment area was chisel plowed to 15 cm after all treatments were applied.

In March 2004, a minimum of three bald cypress (*Taxodium distichum* [L.] Rich) were planted in each plot. Additional woody wetland species were planted on April 23-26 of the same year, including willow oak (*Quercus phellos* L.), sycamore (*Platanus occidentalis* L) green ash (*Fraxinus pennsylvanica* Marsh.), and hazel alder (*Alnus serrulata* [Ait.] Willd.). In May 2004, an herbaceous wetland seed mix was applied to the site which included spotted ladysthumb (Polygonum *persicaria* L.), Pennsylvannia smartweed (*Polygonum pensylvanicum* L.), arrowleaf tearthumb (*Polygonum sagittatum* L.), rice cutgrass (*Leersia oryzoides* L.), fringed sedge (*Carex crinita* Lam.), and redtop panicgrass (*Panicum rigidulum* Bosc ex Nees) (Dickinson, 2007).

Sampling and Analysis

Soil samples were taken in 2003 before treatments were applied, and again in 2004 after application. In 2006, 1 ft by 1 ft samples were collected from 0-3 and 20-25 cm depths in each plot (Dickinson, 2007). Standing biomass and O horizon material were removed from the samples. In 2015, three bulk density (BD) samples were extracted at the top of each horizon in the upper 30 cm within each experimental unit, then combined by horizon for chemical analysis. There were two to four three horizons per plot in 2015.

Samples from 2006 and 2015 were tested for TC and TN with an Elementar CN analyzer (Elementar Americas Inc., Mt. Laurel, NJ; Nelson and Sommers, 1996). There is no inorganic C at the site, so TC and OC are the same. Organic matter equivalents of soils at the experiment site were estimated by multiplying percent OC by 1.724 (the Van Bemmelen factor) (Soil Survey Staff, 2014b). Equation 1 was used to determine mass C per horizon, using OC and average BD (Bliss and Maursetter, 2010). Mass soil C was determined using samples taken in "level" portions of the plots rather than in pits and mounds.

$$C_h = C_s D_{bw} M L * 100 \qquad \text{(Eq. 1)}$$

Where C_h represents mass soil OC in a 1-ha area of each soil horizon (Mg C ha^{-1}); C_s is the soil OC percentage divided by 100 (kg kg^{-1}); D_{bw} is the soil BD (g cm^{-3}); M is the percentage by weight of the < 2-mm soil fraction/100 as (kg kg^{-1}); and L is the horizon thickness (cm).

Samples from both sampling years were analyzed for plant available nutrients (P, K, Ca, Mg, Zn, Mn, Cu, Fe, and B) via a Mehlich-1 extraction (Maguire and Heckendorn, 2011). There was one sample per horizon in each plot in 2006 and 2015.

Soils in differing microtopographic positions (pit, mound) in every plot were sampled to approximately 15 cm using a 3.18 cm diameter push-probe. There was a total of 19 mound samples, and 20 pit samples taken where bald cypress survived in 2015. These samples were analyzed for estimated BD, OC and TN. Their BD was estimated by the volumetric core method 3B6a using the probe diameter and layer depth (Soil Survey Staff, 2014c). One sample was taken in each microtopographic location in each plot to minimize disturbance.

Time comparison data were examined by paired t-tests using the statistical software JMP (SAS, Cary, NC) and $\alpha = 0.05$. Paired t-tests with delta values (2015 value subtracted by 2006 value) were used to test if there were differences between years or sampling depths (null hypothesis: delta value is equal to 0, or no change). Delta values were tested for normality and equal variance using a combination of visual/graphical analysis and tests. Delta value sets that met normality and equal variance assumptions were examined with an overall one-way ANOVA to test if the differences in parameters (e.g. increase in

OC) varied by treatment. A Tukey's HSD test was used to contrast means when the overall ANOVA was significant. Delta value sets that rejected normality and variance assumptions were analyzed with a Kruskal-Wallis nonparametric test (Kruskal and Wallis, 1952), followed by the Wilcoxon rank sum test for contrasting treatment means. A paired t-test was also used to test depth effects in BD, TC, and TN between ^Ap (Ap) and ^C, ^Cg, and 2^C (C) horizons. Treatment effects in 2015 were tested using one-way ANOVA and Tukey's HSD, or Kruskal-Wallis and Wilcoxon for non-normal distributions.

Results

Bulk Density

The BD of the Ap horizons of the topsoil treatments were higher than the control and compost treatments ($p < 0.0001$; Figure 3.2). Soil BD did not vary significantly by treatment across the sandy C horizons ($p = 0.8009$). None of the bulk densities measured in Ap or C horizons were presumed to be root-limiting (Weil and Weil, 2017).

Carbon and Nitrogen

In Ap horizons, soil OC increased from 2006 to 2015 by an average of 2.07% ($p < 0.0001$) (Figure 3.3). During this time period, surface TN also increased by an average of 0.13% ($p<0.0001$). These increases in OC and TN did not vary by treatment ($p=0.6413$, $p=0.4615$, respectively). Soil OC in the C horizons did not change from 2006 to 2015 ($p=0.2153$), but soil TN in C horizons decreased by an average of 0.028% from 2006 to 2015 ($p<0.0001$). This decrease did not vary by treatment ($p=0.3517$).

No treatment effects were found for OC in Ap horizons ($p=0.753$) or C horizons ($p=0.114$) by treatment in 2015 (Figure 3.3). There was also no treatment effect on TN in Ap horizons ($p=0.775$; Figure 3.3). As expected, both TC and TN were much higher in Ap horizons than C horizons in all treatments ($p < 0.0001$, $p < 0.0001$, respectively). This decrease in OC and TN from Ap to C horizons did not vary by treatment (p=0.7512 and p=0.7735, respectively). Soil mass C varied by horizon (p<0.0001). Ap and B horizons had greater mass C than C horizons (Table 3.1). Soil mass C did not vary by treatment in Ap, B, or C horizons (0.9404, 0.2903, 0.4506 respectively). There was an average of 13.67 Mg C ha^{-1} in Ap horizons, 15.24 Mg C ha^{-1} in B horizons, and 3.64 Mg C ha^{-1} in C horizons.

Nutrients

In 2015, there was a trend of lower zinc (Zn) in the loam ^Ap horizons than sandy soils (p=0.06) (Table 3.2). The amount of Zn was slightly lower in the C horizons of topsoil treatments compared to the sandy soils. In 2015, there was more manganese (Mn) in C horizons of the topsoil treatments than in the control. Differences between means of ^Ap horizon Mn, Fe, and Zn were difficult to determine due to low sample size and uneven variance.

Changes in Ap horizon plant available nutrient concentrations are shown in Table 3.3. From 2006 to 2015, soil pH decreased (p<0.0001), plant available phosphorous (P) decreased (p<0.0270), Mn increased (p<0.0001), and copper (Cu) decreased (p<0.0018). These changed occurred relatively uniformly across plots and were not significant by treatment (p=0.8650, p=0.5882, p=0.4900, p=0.4772, respectively).

Soil potassium (K) concentrations increased from 2006 to 2015 in Ap horizons (p<0.0004). These changes varied by treatment (p=0.0010). All treatments had an increase in potassium (K) over time, except treatment 4. Treatment 4 was lower than treatments 1 (p=0.0008), 2 (p=0.0079), and 3 (p=0.0118) but similar to treatment 5 (p=0.3033). Soil calcium (Ca) concentration increased from 2006 to 2015 by an average of 747.38 ppm (p<0.0001). The change in Ca varied by treatment (p=0.0015). Treatments 1 and 3 had a higher increase in Ca than treatment 5 (p=0.0027, p=0.0037). Magnesium (Mg) increased in ^Ap horizons from 2006 to 2015 (p<0.0001). The increase varied by treatment (p=0.0065). Treatments 1 and

3 had a higher increase in Mg than treatment 5. Plant available iron (Fe) content decreased from 2006 to 2015 ($p<0.0001$). Soils in treatment 4 lost more Fe than in treatments 1 ($p=0.0200$) and 3 ($p=0.0304$).

From 2006 to 2015 in C horizons there was a decrease in soil pH ($p<0.001$), Zn ($p=0.0296$), Mn ($p=0.0145$), Cu ($p=0.0003$), and Fe ($p=0.0024$). These decreases did not vary by treatment ($p=0.4841$, $p=0.7246$, $p=0.8547$, $p=0.2364$, $p=0.7051$, respectively). Soil P, Ca, and Mg in C horizons did not change between 2006 and 2015 ($p=0.5588$, $p=0.9730$, $p=0.6604$, respectively). Soil K decreased from 2006 to 2015 in C horizons ($p=0.0004$). The means varied slightly by treatment ($p=0.0352$), with treatment 4 losing more K over time than treatment 2 ($p=0.0294$).

Microtopographic Effects

Mounds had higher BD than pits ($p=0.0010$) (Table 3.4). Organic C varied significantly by microtopographic location, with pits having significantly higher OC than mounds ($p<0.0001$). Total N also varied significantly by microtopographic location ($p = 0.0019$), with soil on mounds having less TN than pits.

Discussion

Sandy soils typically have a higher BD than finer particle size soils due to differences in particle packing and can typically support rooting at higher BD levels than clays due to their preponderance of macropores (> 0.05 mm) vs. micropores (Brady and Weil, 2017). At this site, the loamy topsoil plots may have had higher BD than the sands because of minor compaction or infilling of finer particles between sand grains during original construction and subsequent flooding of the wetland. The sand textures are well sorted with very few fines and more resistant to compaction and infilling. C values were almost high enough for mucky-modified textures (Figure 3.3), leading to the relatively low BD values across all plots.

Both TC and TN were much higher in Ap horizons than C horizons in all treatments, and these results agree with other reports that C content usually decreases with depth (Cummings, 1999; Stolt et al., 2001; Fajardo, 2006). After 12 years, compost amendments did not produce higher OC or TN content in surface or subsurface soils than treatments without compost amendment. Increases in Ap horizon OC and TN did not vary by treatment, so the long-term increases are not solely due to the addition of compost or topsoil. The OC may have reached an equilibrium or increased rapidly in all soils due to the relatively wet overall site conditions and inputs of OC due to litterfall, rooting, and OC deposited by flooding. There may have been an initial compost effect on these soil properties that spread to the entire system, but such effects are difficult to detect with only two sampling times (2006 and 2015). Over the 12 years studied, there was litterfall and fine root turnover from the early succession forest seedlings, saplings, and tree vegetation with grasses and forbs beneath, which contributed to soil OC across all experimental units. The litter has been incorporated into the soil by macro- and micro-organisms to form Ap horizons over time. The periodic flooding events contributed floating OM and might also have contributed finely divided organic-rich sediments and possibly some dissolved OC to the wetland, which would contribute to the similarity in OC between treatments. In addition, the extensive remedial soil tillage left the site with favorable soil physical properties. After 12 years, the surface soils had higher OC than the surface soils in younger and more compacted mitigation wetlands in Virginia studied by Fajardo (2006). However, the surface soils at this site are about 5 cm thick and have low BD, so total soil mass C is low compared to other wetlands. In Virginia created wetlands, soil mass C is 47 Mg ha^{-1} to 176 Mg C ha^{-1} (Fajardo, 2006), and natural wetlands in the contiguous U.S. have an average soil mass C of about 720 Mg ha^{-1} (Kern, 1994).

Compost amendments lowered BD and increase TC and TN in the loamy applied topsoils compared to sandy control treatments, but depending on compost rates applied and parameters evaluated, these differences diminished over time as natural OM accumulation and aggregation occurred. These results are consistent with other findings that compost amendments did not have significant effects on bald cypress growth after 10 years at the same experimental wetland (Pietrzykowski et al., 2015). It is possible that higher compost rates would have produced different results but the higher rates may not have been feasible or affordable. Wetlands with drier or more seasonally-fluctuating hydrology may have produced different results as well because of the doughtiness of coarse sand textures that are also low in OC and/or in created wetland sites with much drier hydroperiod regimes.

Plant available nutrients appeared to vary by treatment in 2015 due to texture and associated differences in mineralogy. In 2015, loamy topsoil had lower Zn than sandy soils due to greater clay sorption in ^Ap horizons. The clay particles present in the topsoil horizons may have adsorbed some of the Zn, lowering its extraction by the Mehlich-1 solution; a strongly acidic extract that estimates plant-available nutrients. Loamy topsoil had greater Mn content than the control, possibly because the topsoil contained and adsorbed more Mn originally than the sand dredged from the river bottom. Loamy also topsoil had a higher Cu content than in control plots for similar reasons. Organic matter can form complexes with Cu, which limits its extractability (Hering and Morel, 1988; Benedetti et al., 1996; McBride et al. 1997; Achiba et al., 2009). For example, the loamy soils have a higher cation exchange capacity than the sandy soils, which would lead to higher nutrient adsorption. Also, the topsoil applied most likely contained more Cu, Mn, and Fe than the dominantly quartz sandy parent material. Both Mn and Fe appear to have been mobilized from the Ap horizons and possibly concentrated in the deeper C horizons. The topsoil treatment effect can still be seen 12 years after application. Over time, most plant available nutrients increased in Ap horizons (P, K, Ca, Mg, Mn), possibly due to nutrient cycling in litterfall and nutrient retention by accumulating OM, but Cu and Fe content decreased. The additions of topsoil and compost seem to have affected these changes. For example, there was a larger decrease in Fe content in treatment 4 (topsoil plus compost) than in treatment 3 (compost at 156 Mg ha^{-1}). Over 9 years (2006 to 2015), there was a decrease in K, Zn, Mn, Cu, and Fe in C horizons. The K content was the only nutrient decrease that seemed to vary strongly by treatment, with soils in treatment 4 losing more K than soils in treatment 2.

As for microtopography effects, pits had lower BD, higher TC, and higher TN because they are saturated, if not ponded, most days and collect more OM as litter and floating debris. Microtopography may also help retain litter in a tidal wetland, where flowing surface water might otherwise remove leaf litter and floating debris.

These results largely agree with past research at the same site. Pietrzykowski et al. (2015) found no benefit of treatments (compost or topsoil) to Bald Cypress (*Taxodium distichum* [L.] Rich) growth. The lasting effects over time (from 20013 to 2013) were due to the pit and mound microtopography added to the wetland during construction (Pietrzykowski et al., 2015). Similarly, there are no lasting compost treatment effects on soil properties (color, BD, OC, TN) after 12 years. The topsoil led to higher BD and more hydric soil indicators after 12 years due to the fine texture of the amendment.

Conclusions

Soil physical and chemical properties in this created wetland progressed towards natural wetland properties (low BD, high OC and TN) over 12 years. However, the changes in these soil properties over time were largely not influenced by compost amendments. The addition of fine textured topsoil to the original sandy soils led to higher BD and certain nutrient content increases and decreases over time.

The wetland uniformly increased in OC and TN in the surface over time, and compost and topsoil treatments did not affect the increase. In 2015, there was no treatment effect on soil mass C by horizon. A few C horizons close to the surface (second horizon when there was no B horizon) were high in mass C and comparable to Ap horizons.

The total soil mass C of this site is low compared to natural wetlands, due to low BD and horizon thickness despite high OC. The created wetland in this study was constructed using minimal compaction/vehicle traffic, and ideal hydrology (groundwater inundation as well as flooding from adjacent James River). The original construction/design of the wetland was apparently more important for developing advantageous wetland soil characteristics (low BD, high OC and TN) than compost and topsoil amendments. It is possible that changes in soil properties over time due to treatment would have been noted if higher compost rates were used (>156 Mg/ha).

The results in this specific wetland may not be applicable to created wetlands with high BD or problematic differing hydrologic regimes. This created wetland is a loose, low BD site with ideal hydrology and has received organic additions from tides and established vegetation.

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Tables and Figures

Table 3.1. Mass soil carbon at WWE in 2015 by major horizon and treatment.

Treatment	Mean Mass Soil C
	Mg ha^{-1}
----- Ap horizons (approximately 0-5 cm) -----	
1- Fertilized control	12.44
2- 78 Mg ha^{-1} compost	14.39
3- 156 Mg ha^{-1} compost	13.71
4- Topsoil + 78 Mg ha^{-1} compost	15.45
5- Topsoil only	12.65
----- B Horizons (approximately 5-20 cm) -----	
4- Topsoil + 78 Mg ha^{-1} compost	18.92
5- Topsoil only	12.18
--- C Horizons (approximately 5-30 cm or 20-30 cm) ---	
1- Fertilized control	4.32
2- 78 Mg ha^{-1} compost	4.11
3- 156 Mg ha^{-1} compost	4.31
4- Topsoil + 78 Mg ha^{-1} compost	2.16
5- Topsoil only	1.37

Table 3.2. Average plant-available Mn, Fe, Zn, and Cu content by treatment in ^Ap horizons and in C horizons (including ^C, ^Cg, and 2^C) in 2015. Within columns, significant differences are denoted by differing letters (α= 0.05 significance level).

Treatment	Nutrient			
	Mn	Fe	Zn	Cu
	---------------------------- ppm ----------------------------			
----------- Ap horizons (approximately 0-3 cm) -----------				
1- Control	35.2	34.7	4.0	0.28a
2- Compost at 78 Mg ha^{-1}	61.6	37.4	4.4	0.33a
3- Compost at 156 Mg ha^{-1}	63.8	53.2	4.2	0.35ab
4- Topsoil plus 78 Mg ha^{-1} compost	66.6	43.7	2.3	0.45b
5- Topsoil only	66.4	52.5	2.7	0.48b
--------- C horizons (approximately 25-30 cm) ---------				
1- Control	5.4a	31.1b	1.4a	0.51a
2- Compost at 78 Mg ha^{-1}	9.0ab	52.4a	2.5b	0.77a
3- Compost at 156 Mg ha^{-1}	9.0ab	40.6ab	2.0ab	0.47a
4- Topsoil plus 78 Mg ha^{-1} compost	16.8b	61.2ab	2.7b	0.55a
5- Topsoil only	13.0b	51.5ab	2.7ab	0.56a

Table 3.3. Change in plant available nutrient content from 2006 to 2015 in ^Ap horizons (approximately 0-3 cm) and C horizons (25-30 cm). Letters next to means indicate a significant change from 2006 to 2015 (non-zero delta value). Differences between treatments are denoted by differing letters within each column (α=0.05).

Treatment*	pH	P	K	Ca	Mg	Zn	Mn	Cu	Fe
		ppm							
Ap horizons (approximately 0-3 cm)									
1- Control	-0.89a	2.4a	33.6a	921a	76.4a	1.0	26.1a	-0.5a	-46.7a
2- C78	-1.10a	1.5a	26.0a	747ab	64.5ab	0.6	43.6a	-0.5a	-60.7ab
3- C156	-0.98a	-1.3a	24.3a	966a	79.8a	1.3	49.6a	-0.8a	-32.0a
4- TS+ C78	-1.03a	2.8a	-8.8b	619ab	49.8ab	-0.5	35.5a	-2.8a	-107.4b
5- TS	-1.21a	2.0a	8.8ab	440b	23.8b	0.2	22.3a	-1.6a	-62.2ab
C horizons (approximately 25-30 cm)									
1- Control	-0.54a	-2.8	-3.0ab	23	6.8	-1.3a	-4.0a	-0.1a	-51.2a
2- C78	-1.27a	0.3	-2.8a	-3	1.5	-0.1a	-2.0a	-0.2a	-26.8a
3- C156	-0.48a	3.8	-7.0ab	-45	-2.0	-2.8a	-12.3a	-0.5a	-124.3a
4- TS+ C78	-0.71a	-8.8	-8.0b	53	0.3	-0.9a	-6.4a	-0.4a	-121.2a
5- TS	-1.15a	3.0	-7.0ab	-31	-4.8	-0.9a	-7.0a	-0.5a	-129.5a

* Treatment symbols: C78 = compost at 78 Mg ha^{-1}; C156 = compost at 156 Mg ha^{-1}; TS+C78 = topsoil plus 78 Mg ha^{-1} compost; TS = topsoil only.

Table 3.4. Average bulk density (BD), total carbon (TC), and total nitrogen (TN) in surface by microtopography position. *

	BD	TC	TN
Location	g cm^{-3}	%	
Mound	1.05a	2.39a	0.19a
Pit	0.87b	3.73b	0.26b

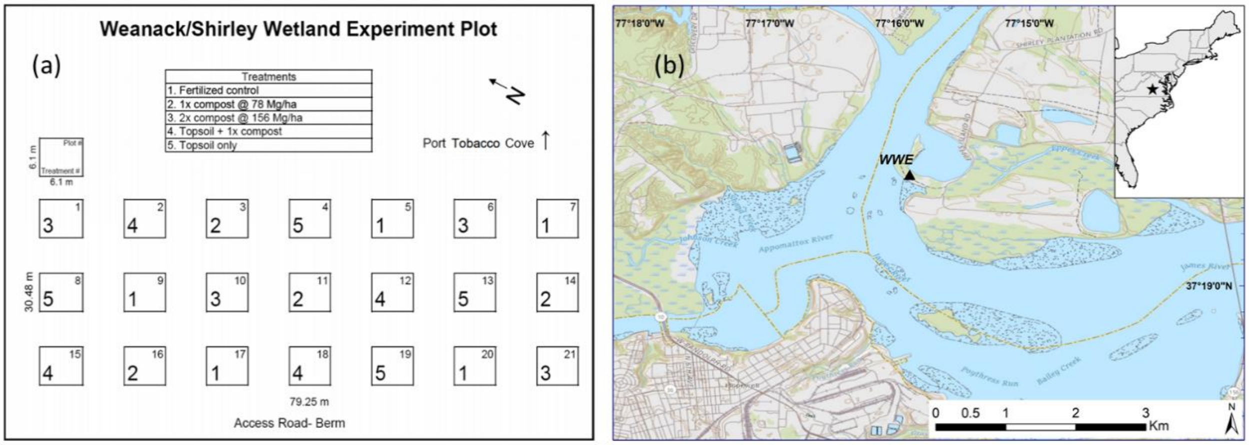

Figure 3.1. (a) The Weanack Wetland Experiment (WWE) research site diagram showing treatments and plot layout (Dickinson, 2007). (b) Location of WWE on the James River in Charles City County, Virginia (credit: Patricia Donovan, Virginia Tech).

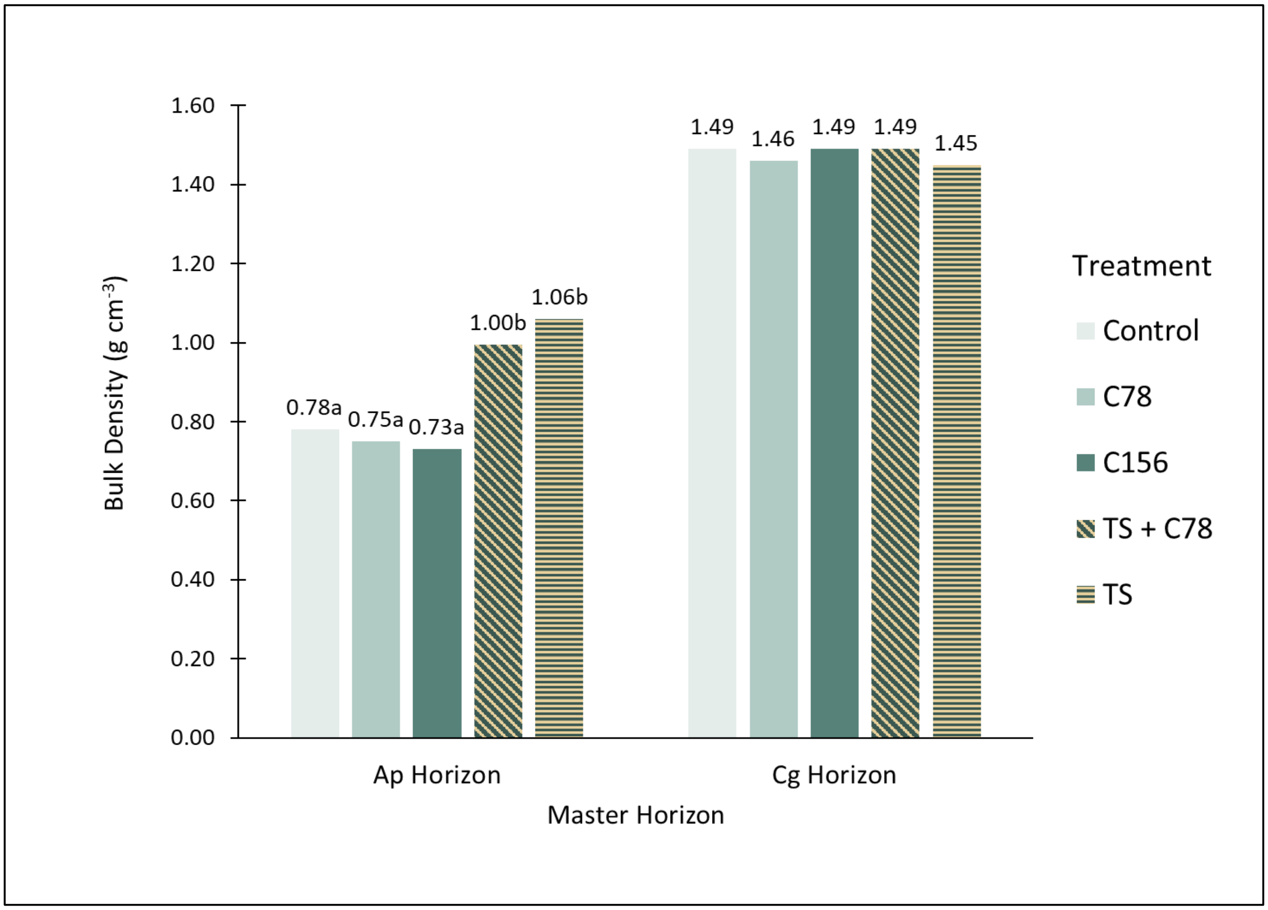

Figure 3.2. In 2015, average bulk density (BD) across treatments varied significantly by treatment in Ap horizons (α= 0.05). Ap horizons in the sand derived Ap horizons had lower BD than Ap horizons in loam. There was no difference across Cg horizons. Treatment symbols: C78 = compost at 78 Mg ha^{-1}; C156 = compost at 156 Mg ha^{-1}; TS+C78 = topsoil plus 78 Mg ha^{-1} compost; TS = topsoil only.

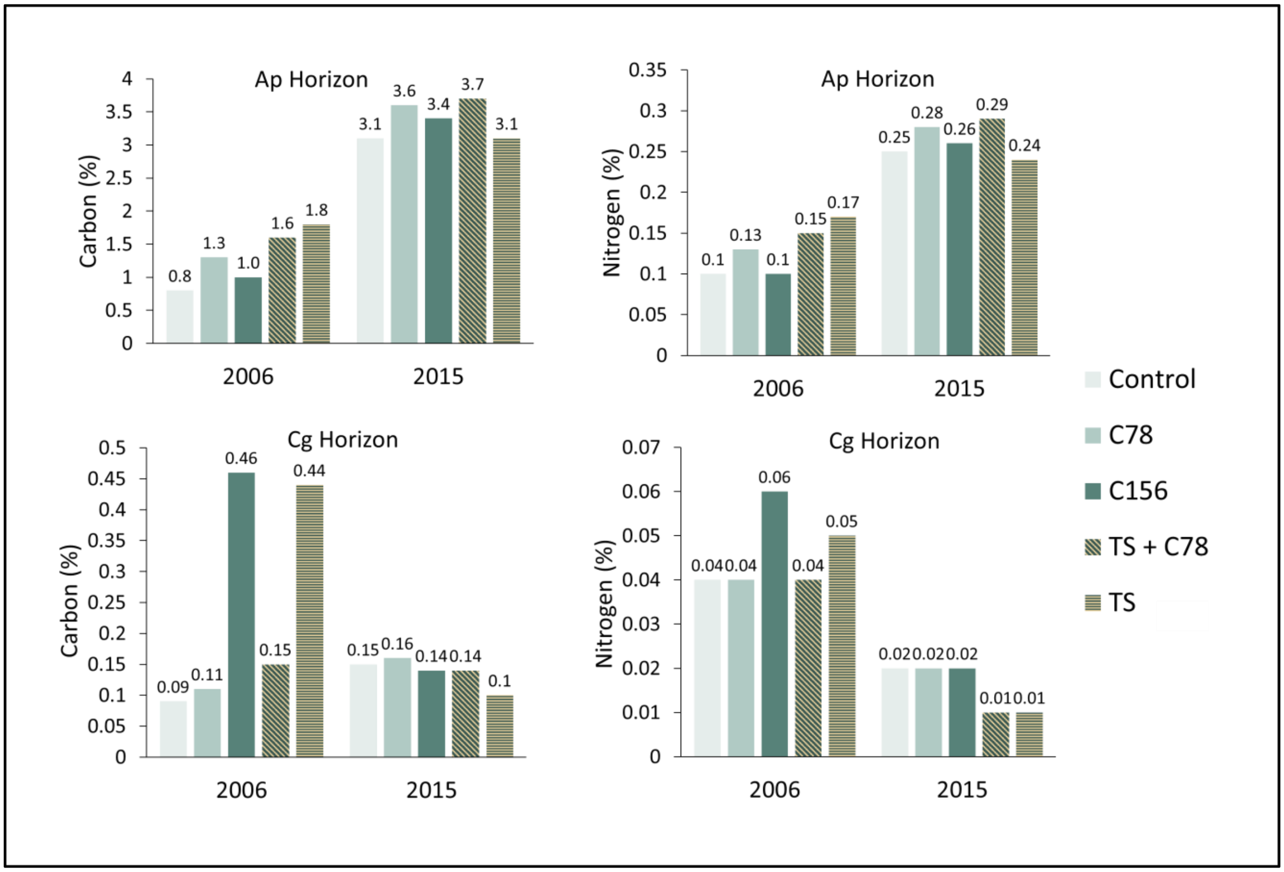

Figure 3.3. Average total organic carbon (OC) and nitrogen (TN) contents in ^Ap and C horizons in 2006 and 2015. In ^Ap horizons, OC and TN increased over time. These increases did not vary by treatment. In C horizons, OC remained the same over time, and TN decreased independent of treatment. Treatment symbols: C78 = compost at 78 Mg ha^{-1}; C156 = compost at 156 Mg ha^{-1}; TS+C78 = topsoil plus 78 Mg ha^{-1} compost; TS = topsoil only.

4. **Effects of Compost Amendments on Virginia Created Wetland Soils 14 Years after Application**

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Abbreviations: BD: bulk density; HSFI: hydric soil field indicators; OC: organic carbon; OM: organic matter; TN: total nitrogen

Abstract

Recently created mitigation wetlands often have lower surficial organic carbon (OC) and higher bulk density (BD) than natural wetlands and may not meet hydric soil field indicators (HSFI). This study describes soil morphology, BD, OC, soil mass C, and plant available nutrients in the upper 30-cm of a fine-textured created wetland in the Coastal Plain of Virginia. The site was created in 1996 by excavating 45-60 cm of surface soil down to a fine-textured subsoil. Five different rates of yard waste compost were applied in 2002 (0 Mg ha^{-1}, 56 Mg ha^{-1}, 112 Mg ha^{-1}, 224 Mg ha^{-1}, and 336 Mg ha^{-1}). In 2016, we described and sampled soils by horizon to 30 cm and compared them with earlier 2003 descriptions and samples. The abundance of HSFI A11 and F3 increased between 2003 and 2016. Ap horizon BD decreased with increasing compost rate, while OC and total nitrogen (TN) increased. There was no difference between 224 and 336 Mg ha^{-1} compost rates in BD, OC, or TN. Soil BD at 13-23 cm was lower than the BD at 23+ cm, which was root limiting in many plots. Soil BD, OC, and TN below surface horizons were not affected by compost treatments. Soil mass C in surface horizons increased with compost rates up to 224 Mg ha^{-1}. The results suggest that in a compacted wetland soil, high amounts of compost amendments may only affect Ap horizon properties long-term. For long-term effects on BD, OC, and TN, we recommend adding 224 Mg ha^{-1} OM to constructed fine textured wetland soils where topsoil was not fully replaced.

Introduction

Wetland restoration and creation have been used since the 1980's to offset the impacts of human impacts to natural wetlands in the US (Mitsch, 1992; Atkinson et al., 1993; Allen and Feddema, 1996; Brown and Lant, 1999). Where possible, wetland restoration is achieved by filling ditches in previously converted farmland and reconnecting the area hydrology to "waters of the US" (Public Law 92-500, 33 U.S.C 1251). Alternatively, new wetlands can be created when uplands are excavated to bring their surface closer to the water table, or when wetlands are hydraulically connected to a nearby source of surface water (Brinson and Rheinhardt, 1996). This study focused on wetland creation.

Creation of wetlands on uplands sites is necessary when other mitigation methods are not feasible as it is the most difficult type of wetland mitigation to successfully accomplish (Zedler and Callaway, 1999; Brinson and Eckles, 2011). Wetland creation frequently includes mass grading of the local landscape, along with stockpiling and redistribution of the upper soil horizons (Clewell and Lea, 1990; Stolt et al., 2000; Bruland and Richardson, 2005). A common wetland creation technique involves excavating upland soil to lower the new surface to at, or just above, the existing water table to achieve wetland hydrology. This method of construction often results in a finer surface texture due to exposure of clay enriched subsoil horizons, especially when there is no topsoil replacement (Stolt et al., 2000). Compaction of soils is also intentional at many wetlands that are built with a "perching design" to create epiaquic conditions and minimize net groundwater losses (Whittecar and Daniels, 1999). Wetlands created with these construction methods have historically had low total carbon (TC) (Bishel-Machung et al., 1996; Whittecar and Daniels, 1999; Stolt et al., 2000; Fajardo, 2006), and high bulk density (BD) (Bishel-Machung et al., 1996; Campbell et al., 2002). For example, in created palustrine wetlands, it may take as long as 300 years for soil to accumulate the same TC in the top 0-5 cm as a natural wetland, and 70 years to develop similar low surface BD as a natural wetland (Hossler and Bouchard, 2010).

Past research has shown that organic matter (OM) amendments lower BD in created wetlands (Bishel-Machung et al., 1996; Collins et al., 1997; Bruland et al., 2009). The determination of an appropriate loading rate of OM and other soil amendments is an important management decision to consider when designing a created wetland.

Soil structure, including aggregate stability, is an important physical property of soils and is affected by wetland creation methods. Compaction during construction traffic on moist, loose soils can result in a traffic pan with platy soil structure, which may pose problems for plant roots and water infiltration (Fajardo, 2006). Construction-related compaction reduces the amount of soil structure and associated macropores, which affects water holding capacity (McIntyre, 1974; Petru et al., 2013). Poor soil structure in created wetlands limits the accumulation of TC. There are fewer macroaggregates (>250 µm) in created wetland soils than natural wetland soils, and the amount of macroaggregates in wetland soils is positively correlated to biomass and soil OC (Hossler and Bouchard, 2010). Over time, soils in created wetlands should accumulate OM and increase in OC, developing stronger soil structure compared to initial conditions. Soil structure and BD are important to the success of created wetlands because these properties may affect both wetland vegetation (e.g. root-limiting compaction) and hydrology (e.g. restrictions to water movement).

Wetland (hydric) soils are identified in the field by hydric soil field indicators (HSFI) (USDA-NRCS, 2017). The HSFI's use specific soil morphological characteristics that are only associated with wetland soils in order to identify hydric soils in the field. Newly created wetland soils might not meet a HSFI if they have not had enough time to accumulate OM or develop dark surface colors or redoximorphic (redox) features or if they have a problem parent material. In contrast, compacted horizons may develop redoximorphic features very rapidly because of low porosity.

When a created wetland cannot provide essential nutrients (particularly N and P) at high enough levels, the wetland may not achieve ecosystem functions equivalent to local natural wetlands (Craft et al., 1991; Langis et al., 1991). Craft et al. (1998) reported that it may take some created marsh wetlands 15-30 or more years to develop total-N and soil OC pools equivalent to that of similar types of natural wetlands. Organic matter amendments have been reported to increase soil nutrient content when added to created wetlands (Stauffer and Brooks, 1997 Bailey et al., 2007; Sutton-Grier et al., 2009). Soil nutrient contents (P, K, Mg, Mn, Ca) in created wetlands may increase over time following OM accumulation (Ballantine and Schneider, 2009). However, studies also report that soil nutrient contents decrease two or more growing seasons after OM amendment (Anderson and Cowell, 2004; Sutton-Grier et al., 2009).

Adding organic amendments (e.g. leaf compost, yard-waste compost, food processing waste, forest products) to created wetland soils provides an electron source for Fe-reducing bacteria and can increase soil structure formation, porosity, water holding capacity, and nutrient contents (Stauffer and Brooks, 1997; Stolt et al., 1998; Bruland and Richardson, 2004). Carbon (C) sequestration is higher in some wetlands than other environments (Wetzel, 1992; Collins and Kuehl, 2001), and because created wetlands are designed to replace natural wetland losses, it is important that they have similar amounts of soil OC. However, created wetlands have historically had lower OC than comparable natural wetlands (Bishel-Machung et al., 1996; Whittecar and Daniels, 1999; Stolt et al., 2000; Fajardo, 2006). Fajardo (2006) found that eight out of 10 created wetlands in Virginia had surface soil OC lower than 2%, even though most of the sites received OM amendments during creation. Adding OM to created wetlands increases soil OC in the short-term (less than five years after creation) but may not have an effect on long-term OC depending on rate and site hydrology (Anderson and Cowell, 2004; Sutton-Grier et al., 2009). High OM loading rates may be necessary for some created wetlands to provide resulting long-term positive effects on soil OC accumulation.

Bergschneider (2005) evaluated different OM loading rates at two experimental sites in the Coastal plain of Eastern Virginia (i.e. the same CCW sites studied here). The 112 Mg ha^{-1} loading rate of yard-waste compost was optimal for soil properties (HSFI, redoximorphic feature development, BD, nutrient content) and a positive hydrophytic vegetation response two years after application (Bergschneider, 2005; Bailey et al., 2007; Bruland et al., 2009). The higher compost rates could not be adequately incorporated into the soil, which caused differences in plot elevation and relative aeration/redox (Bergschneider, 2005). Soils beneath the 224 Mg ha^{-1} and 336 Mg ha^{-1} loading rates had higher redox potentials than the other treatments (Daniels et al., 2005). Soil surface elevation (an average difference of 11 cm between control treatment and 336 Mg ha^{-1} treatment plots), along with saturation and inundation, were more important on soil and vegetation properties than compost amendments in the early years at this wetland (Bailey et al., 2007). The higher compost rates (224 Mg ha^{-1}, 336 Mg ha^{-1}) were not ideal for short term soil or plant growth effects. However, over the long-term, we hypothesized that the higher rates of compost may have positively influenced wetland soil and vegetation as the OM decomposed and elevation differences between plots decreased.

Organic matter amendments generally have positive short-term effects on soil properties in restored and created wetlands. These amendments may also have longer-term effects that converge towards those of natural wetlands (Stauffer and Brooks, 1997; Ballantine and Schneider, 2009; Hossler and Bouchard, 2010), or they may have diminishing or no effects in the long-term (Bishel-Machung et al. 1996, Shaffer and Ernst 1999, Anderson and Cowell; 2004; Sutton-Grier et al., 2009). Therefore, the objectives of this study were to record and explain long-term changes in soil morphological, physical and chemical properties due to compost addition and subsequent soil genesis at the Charles City created wetland; and to recommend an optimal OM loading rate for long-term wetland soil properties.

Methods

Experiment Site

The 19.3 ha Charles City Wetland (CCW) created wetland is located on the Kinney (Claddagh) Farm in Charles City County, Virginia (Bergschneider, 2005; Figure 4.1). This wetland was initially created in 1996 to compensate for forested wetland loss due to road construction by the Virginia Department of Transportation.

The original soil at CCW was mapped as 80% Newflat silt loam, 0-2% slopes, on a terrace of the Chickahominy River (Hodges and Thomas, 2005). Newflat soils are somewhat poorly drained members of the fine, mixed, subactive, thermic family of Aeric Endoaquults (Soil Survey Staff, 2014a). Included in the area are 7% Chickahominy soils, poorly drained members of the fine, mixed, semiactive, thermic family of Typic Endoaquults. The construction design involved excavating about 45-60 cm of surface soils (O + A + E horizons), with little to no topsoil return. This left a silty lower E, or clayey Bt or Btg horizon high in shrink-swell clay exposed at the surface over most of the site. The upper part of this soil became extremely compacted and dense due to the use of heavy machinery during construction of the wetland (Bergschneider, 2005).

At CCW there are two separate experiments that are labeled CCW-Dry at 37.343902N, 76.926898W and CCW-Wet at 37.343569N, -76.926034W. The two experiments were separated based on differing hydrophytic vegetation and hydrology observed in 2002. The CCW-Dry experiment did not meet wetland vegetation criteria and was dominated by sericea lespedeza (*Lespedeza cuneata* [Dum. Cours.] G. Don) and beaked panicgrass (Panicum anceps Michx). In 2003 the CCW-Wet experiment was dominated by hydrophytic vegetation (Typha latifolia L., Scripus spp., Carex spp.). The CCW-Dry experiment was set up as a completely randomized design, and the CCW-Wet experiment was set up as a randomized complete block design. The CCW-Wet experiment was split into four blocks along a slight local contour (< 1%) and the blocks were separated to adjust for local differences in site wetness (Figure 4.2). Each experiment has 20 plots, each 4.6-m by 3.0-m, separated by 3.0 m alleyways.

Site preparation of the experiment area in June, 2002 included the removal of existing vegetation and ripping the soil to 15 cm. The OM amendment applied in July, 2002 was a mixed wood and yard-waste compost (Table 4.1). There were five different treatment levels (treatment 1 = 0 Mg ha^{-1}, treatment 2 =

56 Mg ha^{-1}, treatment 3 = 112 Mg ha^{-1}, treatment 4 = 224 Mg ha^{-1}, and treatment 5 = 336 Mg ha^{-1} on a dry weight basis) with four replicates per treatment in each experiment (Figure 4.2). The highest rate of compost (treatment 5) is comparable to maximum application rates summarized in a review paper by Khaleed et al. (1981). The yard-waste compost could not be fully incorporated into the mineral soil surface in treatments 4 and 5 because of the thickness of the organic amendment on first conventional tractor disking effort, so further incorporation was attempted using a garden tiller to 10 cm. The high rates of compost in treatments 4 and 5 made the original pre-seeding surface elevation 10 to 15 cm higher than the other treatments. In December 2002, five pin oak (*Quercus palustris* Muenchh.) and five river birch (*Betula nigra* L.) seedlings were planted in each plot. A limited number of trees were damaged by rodents and deer during the first winter and were replaced in March and May of 2003. Low wire fencing was added to protect against further herbivory. In 2016, there was an average of 4 river birch and 4 pin oaks in each plot at CCW-Dry, and 4.5 river birch and 3 pin oaks per plot at CCW-Wet.

Sampling and Analysis

In the fall of 2003 and the fall of 2016, one randomly located ‘mini-profile’ (to 30 cm) was described per plot. Horizon names, depths, boundaries, texture, moist matrix color, structure (grade, shape, and size classes), moist consistence, and redox features (type, percent abundance, location, and color) of the mini-profiles were described according to USDA standards (Schoeneberger et al., 2012), and hydric soil field indicators (HSFI) were assigned (United States Department of Agriculture, Natural Resources Conservation Service, 2017).

In 2003, BD of high OM surface horizons was measured using the compliant cavity method 3B3a (Soil Survey Staff, 2014b; Bergschneider, 2005). By 2016, the original compost amendments had decomposed and formed mineral A horizons, so BD was measured by the volumetric core method 3B6a (Soil Survey Staff, 2014b). In October (CCW-Dry) and November (CCW-Wet) of 2016, two samples were extracted per plot with a BD hammer and 5-cm rings to determine the BD in each horizon in the upper 30 cm. All plots were sampled for BD at 0-2 in in September, 2016, and plots with Ap horizons deeper than approximately 7 cm were sampled at an additional depth- the lower 5 cm of the Ap. The Ap horizons were sampled at two depths to account for possible changes in C within the Ap horizon. These separate parts (upper and lower) of the Ap horizon were labeled as Ap1 and Ap2. Particle size distribution of each sampled horizon was analyzed by the hydrometer method (Gee and Bauder, 1986).

For chemical analysis, the two BD samples per horizon were combined into a composite sample. An Elementar CN analyzer (Elementar Americas Inc., Mt. Laurel, NJ) was used to determine TC and TN (Nelson and Sommers, 1996). Total C is assumed to equal organic C (OC) because there are no carbonates in the soil (Bergschneider, 2005). Plant available nutrient content of each sample was determined using a Mehlich-1 extraction (Maguire and Heckendorn, 2011). Plant available nutrients and cations analyzed include P, K, Ca, Mg, Zn, Mn, Cu, Fe, B, and Al. Equation 1 was used to determine mass C per horizon, using OC and average BD (Bliss and Maursetter, 2010).

$$C_h = C_s D_{bw} M L * 100 \qquad \text{(Eq. 1)}$$

Where C_h represents mass soil OC in a 1-ha area of each soil horizon (Mg C ha^{-1}); C_s is the soil OC percentage divided by 100 (kg kg^{-1}); D_{bw} is the soil BD (g cm^{-3}); M is the percentage by weight of the < 2-mm soil fraction/100 (kg kg^{-1}), and L is the horizon thickness (cm).

Outside of, and directly adjacent to each experiment are four external 'pseudo-control' plots (i.e., untreated except for the planting of trees) that represent the experimental soils prior to the June 2002 tilling. Two of these external reference plots were sampled at each experiment. Soil descriptions were made, then BD samples were taken and combined for OC and TN. Results are reported in Appendix F but were not analyzed against treatment 1 (control) because sample size was low (n=2).

Time comparison data were examined by paired t-tests using the statistical software JMP (SAS, Cary, NC) and $\alpha = 0.05$. Paired t-tests with delta values (e.g. 2016 value subtracted by 2003 value) were used to test if there were differences between years or sampling depths (null hypothesis: delta value is equal to 0, or no change). Delta values were tested for normality and equal variance using a combination of visual/graphical analysis and tests. Delta value sets that met normality and equal variance assumptions were examined with an overall one-way ANOVA to test if the differences in parameters (e.g. increase in OC) varied by treatment. A Tukey's HSD test was used to contrast means when the overall ANOVA was significant. Delta value sets that rejected normality and variance assumptions were analyzed with a Kruskal-Wallis nonparametric test (Kruskal and Wallis, 1952), followed by the Wilcoxon rank sum test for contrasting treatment means. Treatment effects in 2016 were tested using one-way ANOVA and Tukey's HSD, or Kruskal-Wallis and Wilcoxon for non-normal distributions. Regression analysis was used for data that had more than one sampling time (i.e. BD, OC), and where regression assumptions were not violated. Regression models were chosen based on lowest root mean square error (RMSE) and highest R^2 value.

Results and Discussion

In 2003 and 2016 the soils at CCW were described with the sequence Ap-Btg, Ap-BAg-Btg, Ap-Bg-Btg, or Oe-BA-Btg (Figure 4.3, Figure 4.4). In 2003, there were 7 plots total in treatments 4 and 5 that had an Oe instead of an Ap horizon at CCW-Wet. No Oe horizons were described in 2016. Over time, the compost additions (Oe horizons in some plots) were decomposed and mixed into lower soil by soil fauna, which minimized plot elevation differences described by Bergschneider (2005) in 2003. In 2003, there were 14 plots at CCW-Dry, and 11 plots at CCW-Wet that had a BA horizon. Most of the remaining plots were in treatment 1 or 2 and had only an Ap and Btg horizon (Or Oe and Btg). Across both sites, the Ap and BAg horizons formed in all treatments. At CCW-Dry, Bg horizons were described in treatments 4 and 4. These Bg horizons were lighter in color than the Ap (which was approximately 7.5YR 2.5/1 due to compost, as opposed to BAg horizons which were similar in color to Ap horizons but had different structure grade or shape. At CCW-Wet, Bg horizons were described at least once in every treatment at

CCW-Wet and were due mainly to different structure (moderate subangular blocky). BAg horizons usually had weak structure and a color similar to the overlying Ap. The bottom of the BAg (or Bg) horizons usually represented the tillage depth. Several tillage/disking efforts were made at the site before compost was applied, including deep ripping by a chisel plow, a forestry disk attempt that was observed to be inadequate, ripping with a root rake to 15cm, and finally, rototilling (Daniels et al., 2004; Bergschneider 2005; Bailey et al., 2007). These tillage/plowing efforts helped loosen the soil to form the surface Ap and BAg (or Bg) horizons.

At CCW-Dry in in November 2003, Ap horizon color varied from 10YR 5/2 in the control plots with no added compost to 10YR 2/1 in the highest compost loading rate (Table 4.2). Ap horizon value decreased with compost loading rate up to treatment 4 ($p= 0.0008$), Treatments 4 and 5 had the same Ap horizon value of 2. The compost was black in color when applied, so after one growing season (compost was applied in July 2002) some of the compost decomposed into humus and lowered Ap color value in treatments 2 and 3. In treatments 4 and 5, the described Ap (or Oe) horizon was primarily unincorporated compost. In 2016, CCW-Dry Ap horizons in CCW-Dry were described as having 10YR hue and a mean chroma of 1.8, and value decreased with increased compost rate ($p= 0.0010$) (Table 4.3). CCW-Wet Ap horizons had a hue of 7.5YR or 10YR, a mean chroma of 1.7, and value decreased with increasing compost loading rate ($p= 0.0036$). Treatments 4 and 5 were similar in color to each other, and both had lower chroma than treatments 1 and 2. There were three plots at CCW-Dry, and six plots at CCW-Wet that developed Apg horizons by 2016. These Apg horizons had high value and low chroma matrix color with $\geq$ 2% redox concentrations. The Apg horizons also occurred in treatments 1 through 3, but not in treatments 4 and 5, where the OM/humus led to a dark (low value) soil color, and because there were not enough distinct redox concentrations.

In 2003, all BAg horizons had a color of 10YR 5/1 or 5/2, occurred below the tilled zone, and did not differ by treatment. In 2016, the second horizon was not consistently described as within or below the tilled zone. Plots with a Bg horizon were in treatments 4 and 5. The very dark (7.5YR 2/1) surface horizons in these plots had a distinctly different Bg horizon beneath, whereas plots with less compost added had a transitional horizon between the Ap and Btg. Color contrasts of second horizons included BAg and Bg horizons, so because some plots lacked a transitional horizon there were no differences between treatments.

All Btg horizons (around 20 to 30 cm depth) were described as N 6/ (neutral gray) (Bergschneider, 2005). The gleyed Btg horizons in 2003 represent the depth of the original water table pre-excavation. In 2016, B horizon (including Bt and Btg) hues were described as either 10YR or 2.5Y hue. The B horizon value and chroma did not differ by treatment (p=0.7096, p=0.3724).

Soil colors at CCW-Wet followed similar patterns as at CCW-Dry. The only color parameter that varied by treatment was Ap horizon value, which decreased with increasing compost loading rate (p= 0.0036). Hues were either 7.5YR or 10YR in Ap horizons, and 7.5YR, 10YR, or 2.5Y in Bt horizons.

At both CCW-Dry and CCW-Wet in 2016, most horizons described had multiple redox concentration colors (e.g. 5YR 5/8, 7.5YR 4/6, and 10 YR6/8), including manganese concentrations (N 2.5/). The different redox concentration hues represent different Fe minerals, such as lepidiocrocite (5YR), ferrihydrite (7.5YR), and goethite (10YR) (Schwertmann and Taylor, 1989; Vepraskas, 2001). Redox concentrations were commonly soft masses, but oxidized root channels and pore linings were also present. Pore linings may have formed where the soil is seasonally saturated (pore linings can form where the water table falls and soils become oxidized) (Megonigal et al., 1996). All plots had one or more horizons with reduced matrixes (value $\geq$ 4, chroma $\leq$ 2). Depletions were not as common in thee Btg horizons as concentrations were. Percent of total redox depletions and concentrations did not vary by treatment at CCW-Dry in Ap horizons (p= 0.5325, p= 0.0735), or in Btg horizons (p=0.2163, p=0.7430) at CCW-Dry (Table 4.3). At CCW-Wet, concentration and depletion contents did not vary by treatment in Ap horizons (0.4060, 0.1860) or Btg horizons (0.7433, 0.1363).

At CCW-Dry, surface soils increased in chroma from 2003 to 2016 (Table 4.4). At CCW-Wet, there was an increase in chroma as well as a decrease in value and content of redox concentrations. There was also an increase in soil chroma in the Btg horizons at both wetlands, and none of the changes in chroma varied by compost amendment. An increase in chroma indicates that the soil has become less grey over time, and this may be due to excavation. The soil horizons were originally 45-60 cm further below ground, so bringing them up to the surface has increased the amount of diffused oxygen, which may have oxidized some Fe^{+2}. There was an increase in redox concentration content at both wetlands in the Btg horizons, possibly also due to bringing the horizons closer to the soil surface. The BD of Btg horizons was root-limiting (Figure 4.5), but there were concentrations along root channels observed in 2016. The two color parameters that appeared to change over time due to compost treatment were value and concentration content at CCW-Wet. Ap horizon value decreased in treatment 2 and increased in treatments 3 and 4, and concentration content had a larger decrease in treatment 2 than in treatments 4 and 5. The Ap horizons at CCW-Wet became lighter (higher value; less dark) in treatments 3, 4, and 5 due to decomposition of the large amount of compost. Surface soil colors in 2003 were black with a value/chroma of 2/1 due to the fresh compost in treatments 4 and 5. Over time, the fresh compost decomposed and was mixed with mineral soil, which had a higher color value. There was a large decrease in percent of redox concentration in the Ap horizons of treatments 1, 2, and 3, possibly because after 13 years there has been net reduction and loss of Fe over time.

In 2003 at CCW-Dry and CCW-Wet, the soils in treatment 3 plots met more HSFI's than other treatments (Table 4.5). Soils in treatments 4 and 5 had grey colors similar to the other plots, but the large unincorporated compost layers above the original surface led to the depleted matrices occurring at a depth greater than 25 cm, which caused them to fail to meet F3. The amount of HSFI's in treatments 1 through 3 decreased from 2003 to 2016 and increased in treatments 4 and 5 as the compost layer decreased in thickness following decomposition.

Overall, there were more HSFI's in 2003 than in 2016. Gley page colors were described in 2003 (N 6/ in Btg horizons), but less gleyed depleted matrices (value $\geq$ 4, chroma $\leq$ 2) colors were found in Btg horizons in 2016. Color values on the neutral or Munsell® gley page have a chroma of 0. This difference (increase in soil chroma over time) led to the F2 Loamy Gleyed Matrix in 2003 but not 2016. The fresh OM added in 2002 accelerated Fe depletion, which may have led to more gley colors in 2003 than in 2016. By 2016, much of the OM had been decomposed and incorporated into the soil, so there was less "fresh" OM than in 2003. The F3 Depleted Matrix indicator was found in many plots in 2003, and in all plots by 2016, due to decomposition of the compost and decreasing depth to depleted matrix in the treatment 4 and 5 plots. In 2003, many of the soils qualified as hydric, however it was unlikely that the indicators were due to soil reconstruction practices, and rather exposure of already reduced soils through excavation (Daniels et al., 2005). Some plots met A11 in 2003 because OM was applied and tilled in, not because of a natural accumulation of OM at the wetland. By 2016, plots in treatments 4 and 5 met A11 following extensive decomposition of the compost and addition of OC to the soil. These results contrast with other published studies such as Vepraskas et al (1999) that found the HSFI F3 forming within five years after wetland construction (by flooding an upland soil). Wetlands formed from excavation to an existing water table will develop HSFI's differently (and possibly meet fewer indicators over time) than wetlands formed by flooding upland soils.

Particle size analysis in 2016 showed that the soils at CCW were either clay loam or loam texture (Table 4.6). While performing soil descriptions many soils were estimated to be silt loam or loam textures, but particle size analysis via hydrometer method resulted in a higher clay percentage. Clay loam textures in the Ap horizons should be expected because of the original excavation into Btg horizons. There was a mix of angular and rounded rock fragments found in the soil profiles while describing the soils. The native soils formed in alluvium from the Chickahominy River, so it was not surprising to find rounded rocks in the Btg horizons. Angular rock fragments may have been in the yard waste compost because they were found mainly in the plots with compost added (treatments 2-5). A few scattered bits of plastic and other artifacts were occasionally found during sampling. Sand, silt, and clay content did not vary by treatment at CCW-Dry in Ap horizons, possibly because of low sample size and/or high variability. In Ap horizons at CCW-Wet, there was more sand in Ap horizons that received 336 Mg ha^{-1} than those that received none or 56 Mg ha^{-1} compost. Therefore, there may have been some soil (especially 0.05-2mm) mixed in to the yard waste compost. Another explanation for the slight differences in texture is that the site may not have been uniformly excavated down to Btg horizons. Lower clay E horizons above the original Btg may not have been fully removed.

At CCW-Dry there was no change in BD between Ap1 and Ap2 layers within soil profiles (p=0.4863), so Ap1 and Ap2 horizons are grouped together as Ap for analysis. In the Ap horizon at CCW-Dry, there was a long-term effect of a decrease in BD with increasing compost amounts ($p< 0.0001$) (Figure 4.5). These results agree with other studies that have found a decrease in compaction with OM amendments (Khaleel et al. 1981, Bishel-Machung et al., 1996; Collins et al., 1997; Cogger 2005, Bruland et al., 2009). At CCW-Wet, Ap2 horizons had a mean BD 0.14 g cm^{-3} higher than Ap1 horizons ($p= 0.0005$). In both Ap1 and Ap2, BD decreased with increasing compost loading rate ($p< 0.0001$, $p= 0.0004$). The difference between Ap1 and Ap2 at CCW-Wet was likely because of slower decomposition due to inundation. The wet conditions inhibited OM decomposition, so there was coarser (freshly deposited) OM at the surface in CCW-Wet, which created a lower BD in the Ap1. On year after compost amendment in 2003, Bruland et al. (2009) found that BD in treatment 2 plots was lower than in treatment 1. Thirteen years later, there is no difference in BD between treatments 1 and 2 at CCW-Wet. The wetter conditions at this side of the wetland have led to more OM accumulation and/or less OM oxidation than at CCW-Dry, where there is a long-term difference between treatments 1 and 2. After > 10 growing seasons and litter deposition from vegetation (such as the pin oaks and river birches), the difference between treatment rates apparently decreased as there was enough moisture to promote OM accumulation.

At CCW-Dry, mean BD in BA and Bt horizons were 1.40 g cm^{-3} and 1.57 g cm^{-3} respectively, and did not vary by treatment (p=0.8376, p=0.3252). The Btg horizons were below 23 cm in these soils, so they were too deep to be affected by the compost amendments. Bergschneider (2005) also did not find a difference in BD within Btg horizons. At CCW-Wet, mean BD in BA and Btg were 1.43 g cm^{-3} and 1.53 g cm^{-3} respectively, and they did not vary by treatment (p=0.5230, p=0.3163). Compost amendments did not lower the BD of BAg horizons, which were around 13-23 cm and were not consistent between plots. Bergschneider (2005) described loose BAg horizons within tilled zones in treatments 3, 4, and 5 in 2003. In 2016, we did not consistently find BAg horizons in the tilled zone between the Ap and Btg. The horizons between the Ap and Btg included loam and clay loam textures, and were usually Bag, but also included Ap2 and Bg. Soil BD did not vary by treatment in Btg horizons, which was expected because they did not have compost mixed in. The high BD of the Btg horizons were potentially root limiting (> 1.45 g cm^{-3} in clay textures). Some root limiting BD's were also found in BA horizons, which means that plant growth may have been limited within 13-23 cm of the soil. Thirteen years after compost amendments were applied, there was a lasting treatment effect on soil bulk density at the soil surface, but not below the Ap horizons.

Soil BD was also sampled in the fall of 2003 by Bergschneider (2005) and compared to the samples taken in 2016. Soil BD in Ap horizons differed from 2003 to 2016 at CCW-Dry (p= 0.0283). Ap horizons in treatment 4 increased in BD over time, while Ap horizons in treatment 1 decreased in BD (p=0.0455). The regression equation that minimized the root mean square error (RMSE) and maximized R^2 was a quadratic equation with compost loading rate as the predictor (p=0.0032) (Table 4.7). Overall, this model explains about 42% of the variability in BD change. At CCW-Dry, soil BD in Ap horizons decreased in treatments 1, 2, and 3, and increased in treatments 4 and 5. A linear regression model with compost as the predictor (p=0.0062) fit the data better at CCW-Wet than a quadratic model (Table 4.7).

Over time, as compost decomposed, the initial very low BD of the compost amendments increased as the volume of compost decreased. In 2003, the surface sampling for BD in treatments 4 and 5 was in approximately 10-12.5 cm of yard waste compost. So, at CCW-Dry, BD decreased in these high OM treatments at the surface only because the 2003 samples were primarily in OM (compost), and the 2016 samples were in mineral soil (Ap horizons). The overall means BD of Ap horizons in treatments 4 and 5 were 0.78 and 0.77 g cm^{-3} respectively, so an increase in BD is not necessarily a negative effect. In contrast, the BD of treatment 1 decreased over time. Plots in treatment 1 did not have compost applied, so they began as a fine-textured subsoil and decreased in BD as OM accumulated at the site in the form of litter.

There was a different pattern in BD changes at the wet experiment compared to the drier experiment. At CCW-Wet, surface soil BD decreased in most of the treatments, while at CCW-Dry surface BD increased in most of the treatments. Only treatments 4 and 5 increased in BD, which isn't necessarily detrimental because their average BD was still low in 2016 (0.65 and 0.58 g cm^{-3} respectively). At CCW-Wet, the wet conditions prevented the original compost from oxidizing/decomposing as rapidly at the drier experiment. The higher plot surface elevation in treatments 4 and 5 at the beginning of the experiment led to an increase in BD over time as the compost decomposed, but the final BD in these plots was still low.

Soil BD in Btg horizons at CCW-Dry and CCW-Wet has remained the same from 2003 to 2016 ($p=0.0860$, $p=0.6236$). Large OM amendments may not affect soils below surface layers, especially if the OM is not well incorporated or the initial BD is root limiting. The BD of many Btg horizons in both sampling years was probably root limiting due to mechanical compaction from multiple passes of plowing equipment.

Organic C did not vary between Ap1 and Ap2 horizons at either experiment, so these horizons were grouped together for statistical analysis. In Ap horizons at both CCW-Dry and CCW-Wet, OC increased with compost loading rate ($p<0.0001$, $p<0.0001$), and TN increased with compost loading rate ($p<0.0001$, $p<0.0001$). Adding compost to the soil had a long-term effect on OC and TN in Ap horizons due to the high OC and TN contents of the compost (Table 4.1). At both sites and for both parameters, there was no difference between the 224 Mg ha^{-1} and 336 Mg ha^{-1} loading rate. The mean OC and TN in treatment 5 was lower at CCW-Dry than CCW-Wet, due to the dry conditions and increased aeration and oxidation of the compost. The wetter experiment retained more of the original compost because of longer ponding and saturation (visual observations). OC and TN did not vary by treatment below Ap horizons. This may be because there was variability in the horizon below the Ap, for example BAg or Bg, and may have been due to uneven incorporation of compost because of initial plot surface differences.

Soil OC and TN were calculated for Ap horizons at five different sampling dates (July 10 2002, Jan 9 2003, Sept 9 2003, Oct 18 2004, Sept 10 2016). The first sampling date was before the compost amendments were applied in July 2002. The remaining four sampling sets were used to compare OC, TN, and C to N ratio (C:N) between treatments over time. Regression assumptions were not met by visual tests (i.e. plotting residual vs predicted) at either CCW-Dry or CCW-Wet, so a Box-Cox transformation on the response (OC, C:N) was used. The change in OC and C:N over time varied by treatment, so multiple linear regressions were used to determine the relationship of time and compost loading rate. Approximate time in months since compost application was used. Both variables (time and compost) were significant predictors of soil OM at CCW-Dry ($p=0.0001$, $p<0.0001$) and CCW-Wet ($p=0.0007$, $p<0.0001$). Regression equations are presented in Table 4.8. Time and compost rate were also significant predictors of C:N at both sites ($p<0.0001$). By 2016, the C:N of Ap horizons was the same across plots at CCW-Dry ($p=0.5965$) and CCW-Wet ($p=0.1506$). In control plots at CCW-Dry, there was a decrease in C:N over time ($p<0.0001$), and OC remained relatively constant with an average of 2.35% ($p=0.4740$). In control plots at CCW-Wet, there was no difference in OC or C:N over sampling time ($p=0.5050$, $p=0.0694$). There was a decrease in C:N at CCW-Dry because of drier conditions during the growing season that would lead to more decomposition (and lowering of C:N) than at CCW-Wet.

The Ap1 and Ap2 horizons did not differ in soil mass C at CCW-Dry (p = 0.9367), so they were grouped together to compare against BA and Btg horizon groups. Two horizons (plots 3 and 16) at CCW-Dry were sampled as a Btg horizon but were more likely a Bg or Bw horizon (high in C%, lower in clay than Btg), so they were grouped with the BA samples for analysis. Mass C in Ap horizons varied with treatment, using an ANOVA test (p<.0001; Table 4.9). The soils with 224 and 336 Mg ha^{-1} compost applied had greater mass C than soils in the control and 56 Mg ha^{-1} treatments. In BA horizons, mass C was higher in treatment 5 plots than treatment 1 plots (p= 0.0499). Mass C did not vary by treatment in Btg horizons (p=0.0963). In treatments 1 and 2, mass C did not vary with soil depth to 30 cm (p = 0.7426, p = 0.0516). Mass C varied by depth in the other treatments. In treatment 3, Ap horizon mass C was higher than in Btg horizons (p = 0.0107), and in treatments 4 and 5, both Ap and BA mass C were higher than in Btg horizons (p=0.0211; p= 0.0300). Total soil mass C by treatment on 2015 and mass C of original compost additions is shown in Table 4.10.

At CCW-Wet, soil mass C is similar throughout the Ap horizon (p = 0.6892), so Ap1 and Ap2 are grouped together for analysis. Mass C varied by treatment in Ap horizons (p<0.0001). Soils that received 224 or 336 Mg ha^{-1} of compost had higher mass C than plots that received 0 or 112 Mg ha^{-1} (Table 4.9). Soil mass C did not vary by treatment in BA horizons (p = 0.3276), or in Btg horizons (p = 0.8586). Total soil mass C to 30cm at CCW-Dry ranged from 34.9 – 117.4 Mg C ha^{-1}, and at CCW-Wet the total soil mass C ranged from 33.2 – 107 Mg C ha^{-1}. These values are similar to other created wetlands in Virginia, whose soil mass C is 47 Mg ha^{-1} to 176 Mg C ha^{-1}.

In 2016, 13 years after treatment application, compost amendments continued to have an effect on plant available nutrients in Ap horizons at CCW-Dry (Table 4.11) and CCW-Wet (Table 4.12). At both sites, Cu decreased with increasing compost loading rate (p=0.0051, p=0.0008). Soil OM can for, complexes with Cu, which limits its extractability (Hering and Morel, 1988; Benedetti et al., 1996; McBride et al. 1997; Achiba et al., 2009). Extractable Fe content also decreased with higher compost rates at CCW-Dry and Wet (p= 0.0055, p= 0.0040). A lower content of soluble Fe^{+2} in treatments 4 and 5 at CCW-Dry, and in treatment 5 at CCW-Wet may be due to initial plot elevation differences when the compost was applied. It is also possible that Fe was forming complexes with the OM in treatments 4 and 5, which lowered the extractability. From an average of five samples (Table 4.1), the initial compost amendment contained 6078 mg kg^{-1} total Fe, but very little of this would have been Mehlich 1 extractable.

In Ap horizons at CCW-Dry, there was a higher concentration of extractable P, K, Ca, Mg, Zn, and B in treatments 4 and 5 than in treatments 1 and 2 (p=0.0374, p=0.0023, p=0.0101, p=0.0050, p=0.0156). In Ap horizons at CCW-Wet there was a similar pattern, with Ca, Zn, and Al increasing with compost rates (p=0.0047, p=0.0143, p=0.0255). There were few treatments effects measured in the BAg and Btg horizons at either site. Compost amendments had a positive effect on plant available nutrients (P, K, Ca, Mg, Zn, B), depending on the general wetness of the site. Treatment 3 is similar to treatments 4 or 5 for only a few plant nutrients (P and B at CCW-Dry; Zn, Fe, Al at CCW-Wet). Overall, treatment 4 (224 Mg ha^{-1} compost) was ideal for increasing plant available nutrients over a long period of time at both the dry and wet experiment sites.

Conclusions

We recommend that compost should be added to created wetlands that are created by excavating into a clayey subsoil, when topsoil isn't replaced, or when the soil is compacted during construction. For long-term (13 years or more) effects on soils in non-tidal created wetlands in the Mid-Atlantic Coastal Plain intended to replace forested wetlands, 224 Mg ha^{-1} appeared to be the compost loading rate after mechanical disking/ripping. This conclusion is primarily based on long-term BD, OC, and plant available nutrients, and also on the formation of lasting HSFIs. Within the first few years of amendment application there may be difficulty incorporating large amounts of compost (>112 Mg ha^{-1}), which creates drier soil conditions (especially in epiaquic conditions where soil isn't well connected to groundwater because of compaction). Initial short-term recommendations based on this research site were for 112 Mg ha^{-1} compost (Bergschneider, 2005; Bailey et al., 2007), and 60-180 Mg ha^{-1} compost (Bruland et al., 2009), and included plot elevation differences which were not apparent over the long-term.

For future research, we recommend investigating long-term interactions of hydrology and compost amendments. Ideal compost rates may depend on water table height and source (i.e. surface water or groundwater). For wetlands that are created to compensate for natural wetland losses, it is assumed that the wetlands are also designed to compensate for loss of wetland functions. Therefore, we advise that long-term effects of amendments be considered in addition to short-term effects to create wetlands that successfully replace natural functions.

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Tables and Figures

Table 4.1. Chemical properties of compost before application to the Charles City Wetland (from Bergschneider, 2005).

Compost sample #	Solids	Organic C	Organic N	C/N	EC
	%	mg kg^{-1}			mS cm^{-1}
1	56	369850	8400	44	0.56
2	60	306800	7200	43	0.66
3	50	381104	8700	44	0.64
4	53	310459	7800	40	1.2
5	53	426627	9100	47	0.74

Table 4.2. Average colors in Ap horizons at CCW-Dry and CCW-Wet in 2003 as described by Bergschneider (2005), including redoximorphic depletions ("Depl.") and concentrations ("Conc."). Within each column under each horizon type, numbers followed by different letters are significantly different (α = 0.05).

	CCW-Dry			CCW-Wet		
Compost Treatment	Value	Chroma	Conc.	Value	Chroma	Conc.
Mg ha^{-1}			%			%
			Ap Horizons (~0-13 cm)			
0	5.0a	2.0a	8.6ab	5.0a	2.0a	6.1ab
56	4.0b	2.0a	14.3a	4.0b	2.0a	11.4a
112	3.0c	1.5ab	3.1bc	3.0c	1.5ab	12.4a
224	2.0d	1.0b	0.50c	2.0d	1.0b	3.0b
336	2.0d	1.0b	0.75c	2.0d	1.0b	1.3b
			Btg Horizons (23-30+cm)			
0	6.0	0.0	18.0ab	6.0	0.0	24.0
56	6.0	0.0	14.3ab	6.0	0.0	23.2
112	6.0	0.0	16.7a	6.0	0.0	21.8
224	6.0	0.0	9.3b	6.0	0.0	17.0
336	6.0	0.0	10.8ab	6.0	0.0	19.3

*Surface horizons at seven CCW-Wet plots in 224 and 336 Mg ha^{-1} loading rates were described as Oe, but are included with Ap horizons for analysis.

Table 4.3. Average colors in Ap and Btg horizons at CCW-Dry and CCW-Wet in 2016, including redoximorphic depletions ("Depl.") and concentrations ("Conc.") by horizon and treatment. Within each column under each horizon type, numbers followed by different letters are significantly different (α = 0.05).

	CCW-Dry				CCW-Wet			
Compost Treatment	Value	Chroma	Depl.	Conc.	Value	Chroma	Depl.	Conc.
Mg ha^{-1}			---- % ----				---- % ----	
	---------------------- Ap Horizons (~0-13 cm) ----------------------							
0	4.0a	2.0	0.0	2.4	4.5a	2.0	0.0	1.8
56	4.0a	2.0	0.4	0.6	4.0a	1.5	1.0	2.3
112	3.0b	2.0	0.8	1.0	3.6ab	1.8	0.0	2.3
224	2.0bc	1.5	0.0	0.0	2.4bc	1.8	0.0	0.5
336	2.25c	1.75	0.0	0.0	2.1c	1.5	0.0	0.0
	---------------------- Btg Horizons (~23-30+ cm) ----------------------							
0	5.5	1.8	4.5	20	5.3	1.4	3.3	17.9
56	5.4	1.6	3.0	18.8	5.3	1.1	7.0	31.4
112	5.3	1.5	6.5	13	5.4	1.0	3.4	25.2
224	5.3	1.0	1.3	20.3	5.5	1.0	4.2	18.2
336	5.0	1.7	4.0	19	5.6	1.4	2.6	18.0

Table 4.4. Changes in soil color (value, chroma, and redoximorphic concentration content) over time. Delta values represent the 2016 minus the 2003 value. Within each column under each horizon type, numbers followed by different letters are significantly different (α = 0.05). Numbers not followed by letters indicate no overall change from 2003 to 2016 (mean delta = 0). “ns” means delta ≠ 0, but doesn’t vary by treatment.

		CCW-Dry			CCW-Wet		
Treatment	Compost Loading Rate	ΔValue	ΔChroma	ΔConc.	ΔValue	ΔChroma	ΔConc.
	Mg ha^{-1}			%			%
		----------------------- Ap Horizons (0-13 cm) -----------------------					
1	0	-1.0	0.0	-6.1	-0.5ab	1.0	-4.4ab
2	56	-0.3	0.0	-13.5	-0.8b	-0.3	-9.1b
3	112	0.0	0.0	-2.1	0.6a	0.8	-10.1b
4	224	0.0	0.0	-0.5	0.4a	0.8	-1.8a
5	336	0.3	0.8	-0.8	0.1ab	0.5	-1.3a
		----------------------- Btg Horizons (23-30+ cm) -----------------------					
1	0	-0.5	1.8ns	2.0	-0.3	1.0	2.5
2	56	-0.8	1.8ns	6.3	-0.8	1.0	16.4
3	112	-0.7	1.7ns	0.0	-0.5	1.0	4.0
4	224	-0.8	1.3ns	10.8	-0.5	0.5	3.0
5	336	-1.3	1.8ns	7.0	-0.3	1.5	-0.8

Table 4.5. Treatments by plot number and their hydric soil indicator status in October 2003 and October-November 2016 at CCW-Dry and CCW-Wet (USDA-NRCS 2017). Indicators used are: A11- Depleted Below Dark Surface; F2- Loamy Gleyed Matrix; F3- Depleted Matrix; and F6- Redox Dark Surface.

	CCW-Dry			CCW-Wet		
Compost loading rate	Plot	2003	2016	Plot	2003	2016
0 Mg ha^{-1}	5	F2, F3	F3	3	F2, F3	F3
	8	F2, F3	F3	9	F2, F3	F3
	11	F2, F3	F3	14	F2, F3	F3
	20	F2, F3	F3	16	F2, F3	F3
56 Mg ha^{-1}	6	F2, F3	F3	4	F2, F3	F3
	10	F2, F3	F3	7	F2, F3	F3
	14	F2, F3	A11, F3	12	F2, F3	F3
	18	F2, F3	F3	19	F2, F3	F3
112 Mg ha^{-1}	4	A11, F2, F6	A11, F3	1	A11, F2, F6	F3
	9	A11, F2, F6	A11, F3	8	A11, F2, F6	F3
	12	A11, F2, F6	A11, F3	15	A11, F2, F3, F6	F3
	19	A11, F2, F6	A11, F3	18	A11, F2, F3, F6	A11, F3
224 Mg ha^{-1}	2	F2, F3	A11, F3	5	F2, F3	A11, F3
	3	A11, F2, F3	A11, F3	6	F2, F3	A11, F3
	7	F2	A11, F3	13	F2	A11, F3
	17	A11, F2	A11, F3	17	F2	A11, F3
336 Mg ha^{-1}	1	F2	A11. F3	2	F2	A11, F3
	13	F2	A11, F3	10	F2	A11, F3
	15	F2	A11, F3	11	F2	A11, F3
	16	F2	A11, F3	20	F2	A11, F3

Table 4.6. CCW-Dry and CCW-Wet mean particle size distribution by horizon and treatment.

		CCW-Dry				CCW-Wet			
Compost	Horizon	Sand	Clay	Silt	Texture Class	Sand	Clay	Silt	Texture Class
Mg ha^{-1}		------------ % ------------				------------ % ------------			
0	Ap	25.0	39.2	35.8	Clay Loam	19.1	47.6	33.3	Clay
	BAg	30.0	35.9	34.1	Clay Loam	28.5	33.6	37.9	Clay Loam
	Btg	20.9	53.4	25.7	Clay	20.3	56.4	23.3	Clay
56	Ap	25.2	44.4	30.4	Clay	20.7	49.6	29.7	Clay
	BAg	26.4	43.3	30.3	Clay	23.9	49.4	26.7	Clay
	Btg	25.4	49.2	25.4	Clay	24.7	54.3	21.0	Clay
112	Ap	29.6	34.1	36.3	Clay Loam	30.5	37.2	32.3	Clay Loam
	BAg	29.8	45.5	24.7	Clay	24.1	43.5	32.4	Clay
	Btg	23.3	56.1	20.6	Clay	21.1	57.2	21.7	Clay
224	Ap	36.1	37.3	26.6	Clay Loam	27.7	31.2	41.1	Clay Loam
	BAg	33.6	31.5	34.9	Clay Loam	24.1	44.4	31.5	Clay
	Btg	26.3	48.9	24.8	Clay	24.0	52.7	23.3	Clay
336	Ap	36.3	31.9	31.8	Clay Loam	42.2	31.1	26.7	Clay Loam
	BAg	28.8	34.5	36.7	Clay Loam	26.8	39.7	33.5	Clay Loam
	Btg	22.9	54.4	22.7	Clay	22.0	50.0	28.0	Clay

Table 4.7. Regression equations for data from two different sampling events (2003 and 2016) that relate compost loading rate to surface soil bulk density.

Site	Equation	RMSE	R^2
CCW-Dry	$\Delta BD = 0.0280 + 0.00145L - 8.64 * 10^{-6}(L - 145.6)^2$	0.202625	0.41786
CCW-Wet	$\Delta BD = -0.179 + 0.0000789L$	0.1372124	0.3481949

ΔBD = change in BD (g cm^{-3}) over 13 years (final – initial)

L = compost loading rate in Mg ha^{-1}

Table 4.8. Regression equations for data from four different sampling events (2003 - 2016) that relate compost loading rate and time to surface soil OC.

Site	Equation	RMSE	Adjusted R^2
CCW-Dry	$\left(\frac{C:N^{-1.882}-1}{-0.000342}\right) = 2917.225 + 0.00673L + -0.0396T$	1.755971	0.721262
CCW-Dry	$\left(\frac{OC^{0.129}-1}{0.0274}\right) = 5.837 + 0.030L + -0.0113T$	1.809036	0.80872
CCW-Wet	$\left(\frac{C:N^{-1.21}-1}{-0.00566}\right) = 81.796 + 0.0173L + -0.0391T$	1.755971	0.721262
CCW-Wet	$\left(\frac{OC^{0.229}-1}{0.0547}\right) = 5.280 + 0.0389L + -0.0134T$	2.327408	0.809298

OC = soil organic carbon (%)
C : N = carbon to nitrogen ratio
T = time since application (months)
L = compost loading rate (Mg ha^{-1})

Table 4.9. Soil mass C by horizon at CCW-Dry and CCW-Wet in 2016. Significant differences in each column for each horizon group by treatment are indicated by differing letters.

	CCW-Dry		CCW-Wet	
Treatment	n	Mean Mass C	n	Mean Mass C
Mg ha^{-1}		Mg ha^{-1}		Mg ha^{-1}
------------- Ap Horizons (0-13 cm) -------------				
0	6	13.47 c	5	10.91c
56	7	19.83 bc	5	17.95bc
112	7	25.49ab	8	17.29c
224	7	32.65a	8	26.33ab
336	8	28.99a	8	32.04a
------------- BAg Horizons (13-23 cm) -------------				
0	4	12.53b	4	21.94 ns
56	4	17.23ab	4	22.89 ns
112	4	16.50ab	4	16.44 ns
224	5	26.43ab	4	24.69 ns
336	5	28.17a	4	18.11 ns
------------- Btg Horizons (23-30+ cm) -------------				
0	4	10.15 ns	4	4.29 ns
56	4	9.10 ns	4	3.56 ns
112	4	9.14 ns	4	3.59 ns
224	3	3.43 ns	4	4.14 ns
336	3	6.12 ns	4	4.34 ns

Table 4.10. Mass C in compost treatments added in 2003, and soil mass C in 2015.

Compost Treatment		CCW-Dry	CCW-Wet
Dry weight	Mass C	Soil mass C to 30cm	
------------- Mg ha^{-1} -------------			
0	0.00	42.89	39.99
56	8.97	61.15	49.10
112	17.95	70.23	54.73
224	35.90	92.75	81.88
336	53.85	97.78	86.95

Table 4.11. Mean plant available nutrient and cation content at CCW-Dry in 2016. Significant differences in each column for each horizon group by treatment are indicated by differing letters.

Treatment	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B	Al
Mg ha^{-1}	--- ppm ---									
	----------------------------------- Ap Horizons (0-13 cm) -----------------------------------									
0	3b	55	987c	295c	2c	69	0.5a	44a	0.3b	138c
56	4b	70	1454bc	371bc	3bc	63	0.5a	60a	0.3b	176abc
112	5ab	74	1883b	406bc	4b	71	0.4a	30a	0.4b	202b
224	9ab	71	3404a	665a	19a	66	0.1b	6b	0.6ab	92a
336	6a	69	3240a	606ab	6ab	66	0.1b	7b	0.7a	124abc
	------------------------------------ BAg Horizons (13-23 cm) ------------------------------------									
0	2	38	745	270	1	49	0.4	37	0.1b	135
56	3	45	995	323	1	43	0.5	45	0.2ab	145
112	2	53	1042	293	1	45	0.5	45	0.2ab	148
224	4	45	1126	295	2	44	0.4	39	0.3a	153
336	3	48	1022	257	1	50	0.4	40	0.3a	155
	------------------------------------ Btg Horizons (23-30+ cm) ------------------------------------									
0	1	24b	418	230	1	17	0.4	42	0.1	299
56	1	30ab	665	325	1	20	0.3	27	0.1	130
112	1	49ab	660	295	0	20	0.4	29	0.1	221
224	1	41a	551	228	1	18	0.4	33	0.2	271
336	2	49a	693	273	1	31	0.4	37	0.2	228

Table 4.12. Mean plant available nutrient content at CCW-Wet in 2016. Significant differences in each column for each horizon group by treatment are indicated by differing letters (α = 0.05).

Treatment	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B	Al
Mg ha^{-1}	ppm									
	Ap Horizons (0-13 cm)									
0	4ab	61	853b	245	2b	62	1	138a	0.2	170b
56	3ab	60	1065b	257	2b	78	1	167a	0.2	202ab
112	2b	50	1190b	262	3ab	81	1	121ab	0.3	200ab
224	5a	84	2361a	364	11a	106	1	78ab	0.3	318a
336	4ab	74	2982a	348	15a	110	0	27b	0.4	273ab
	BAg Horizons (13-23 cm)									
0	2	34	662	213	1	73	1	66	0.2	150
56	2	30	656	208	2	54	1	73	0.2	228
112	2	30	774	288	2	48	1	49	0.2	124
224	3	55	933	310	2	43	1	69	0.2	129
336	3	45	912	244	1	55	1	55	0.3	124
	Btg Horizons (23-30+ cm)									
0	0	23b	456	302	1	29	1	27	0.1	283
56	0	27ab	316	192	1	20	1	28	0.1	414
112	0	24b	324	228	1	16	1	32	0.1	436
224	1	43a	702	374	1	31	0	20	0.1	131
336	1	42a	663	370	1	39	0	20	0.2	192

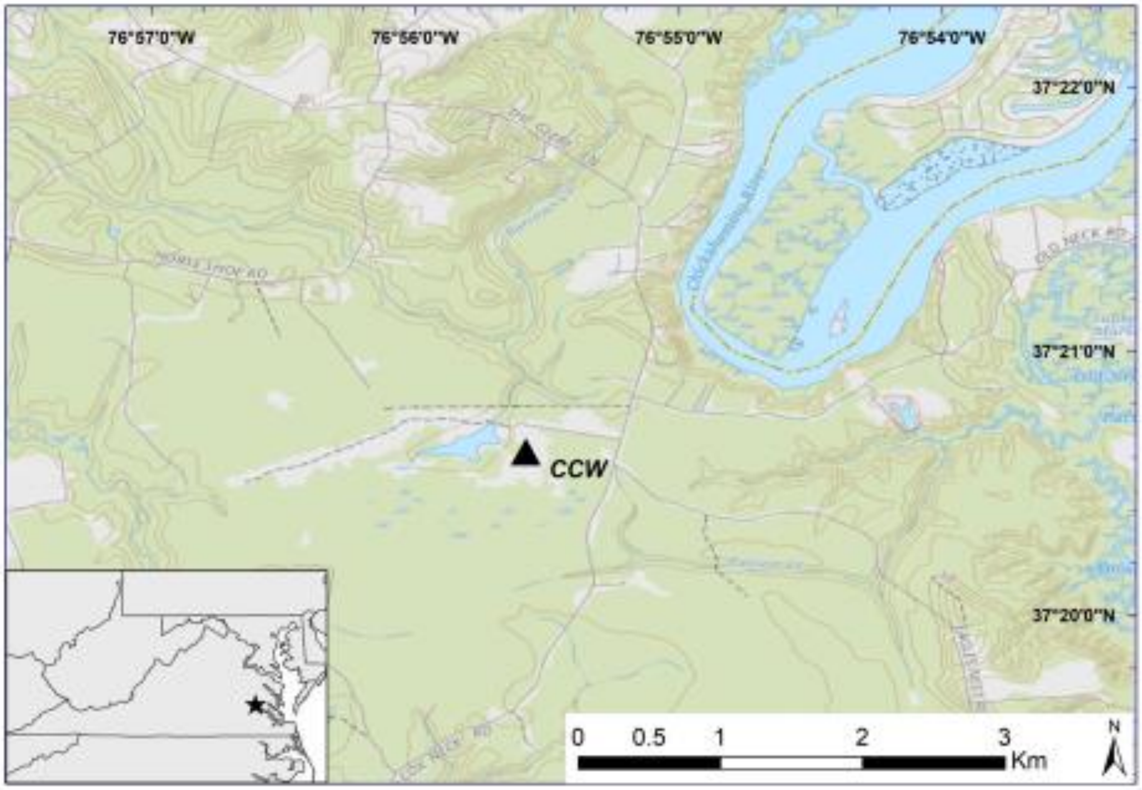


Figure 4.1. Location of the Charles City Wetland in the Virginia Coastal Plain, south of the Chickahominy River.

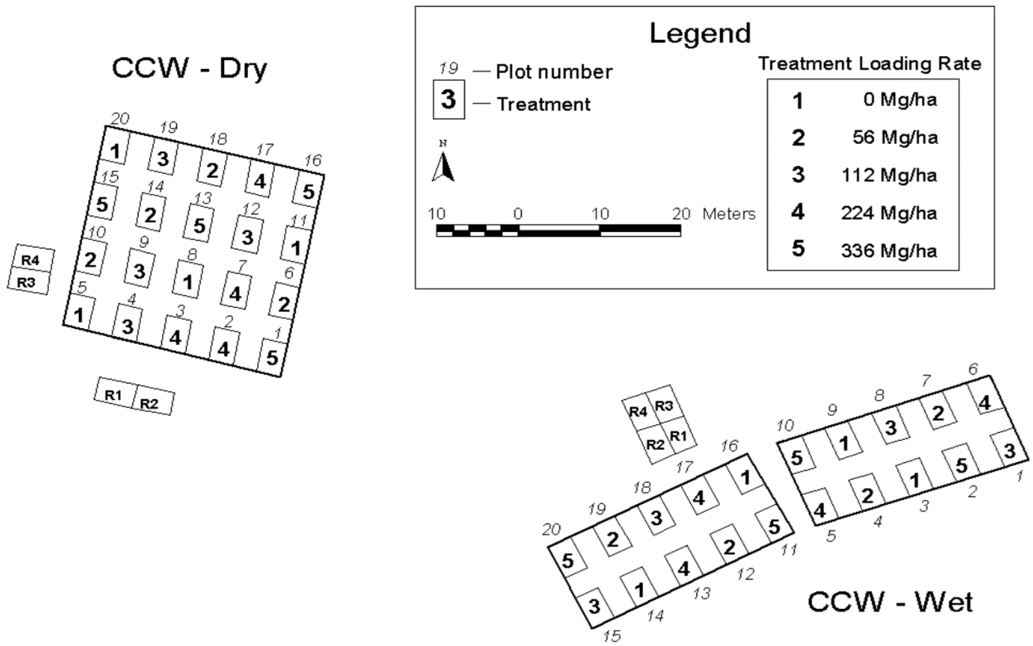


Figure 4.2. Plot diagram of Charles City Wetland. The treatments were applied in 2002 (Bergschneider, 2005).

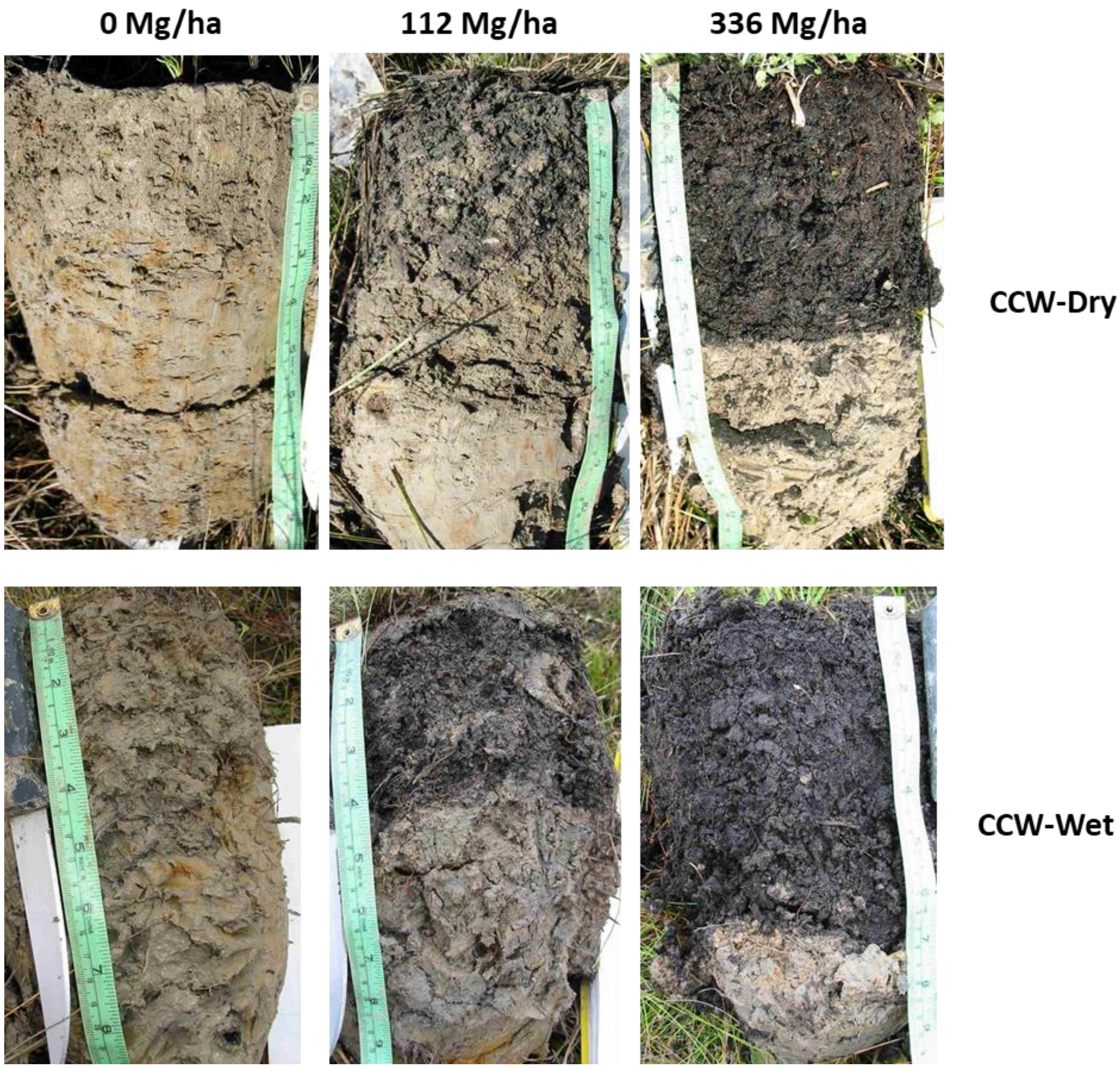


Figure 4.3. Soil profiles at CCW-Dry and CCW-Wet in 2003 (photos by Cara Bergschneider).

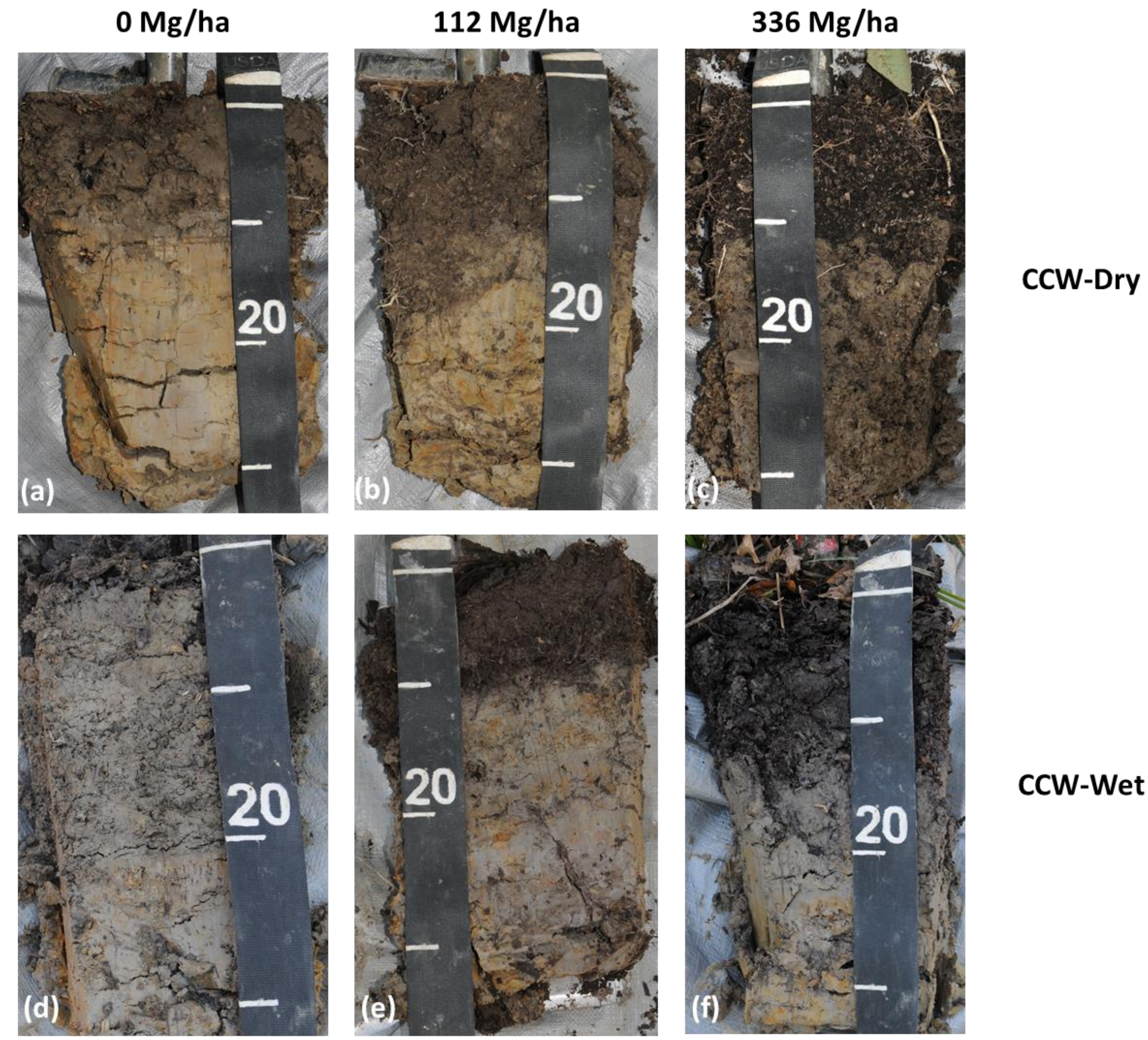
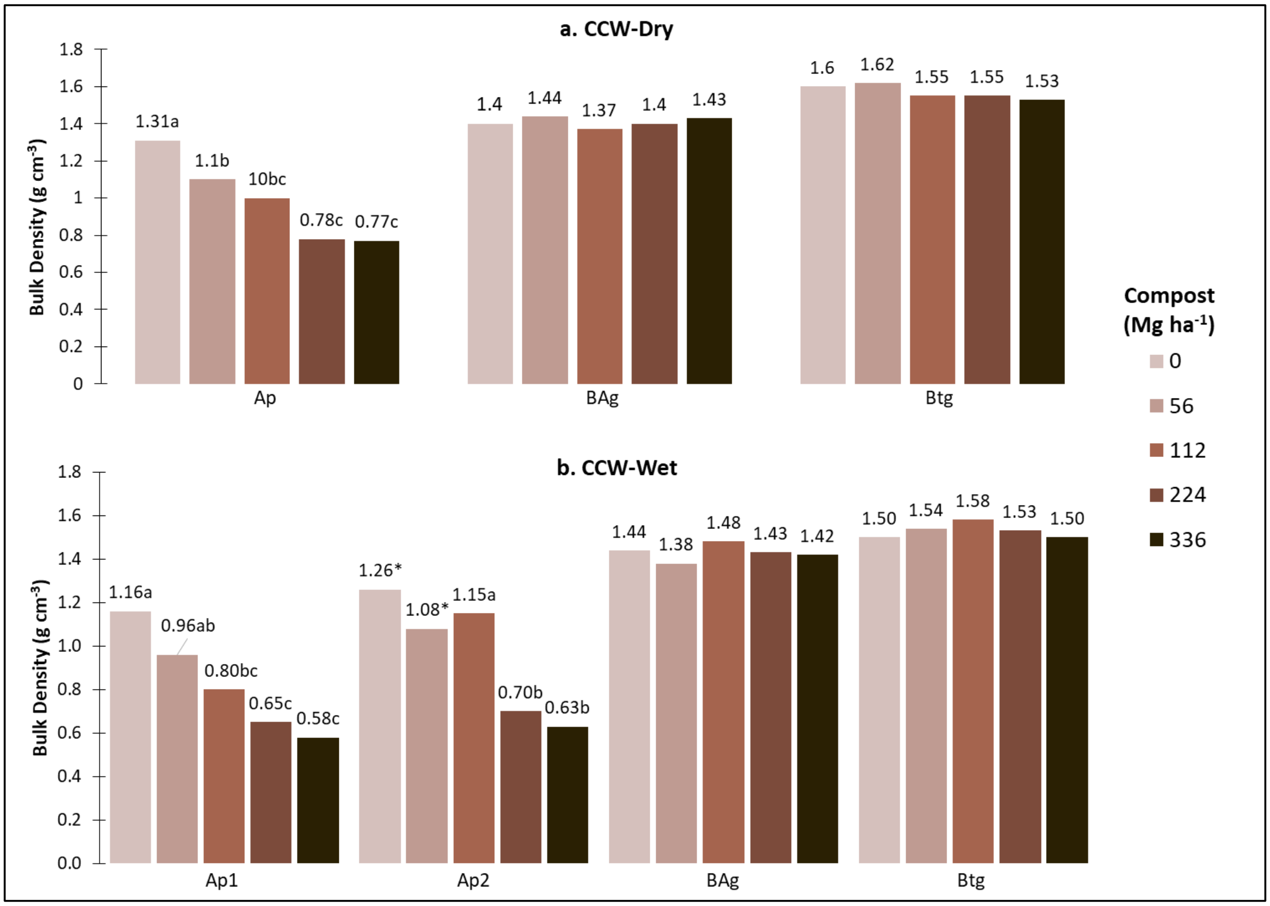


Figure 4.4. Soils in 2016 at CCW-Dry in a) treatment 1, plot 11; b) treatment 3, plot 12; and c) treatment 5, plot 16. Soils at CCW-Wet in in d) treatment 1, plot 9; e) treatment 3, plot 18; and f) treatment 5, plot 10.



*n=2. Samples were not included in means comparison due to small sample size.

Figure 4.5. Soil bulk density at a) CCW-Dry, and b) CCW-Wet in 2016. Differences between treatment means within each horizon group are distinguished by differing lowercase letters (α = 0.05).

5. Soil Organic Matter and Topsoil Effects on Mass Soil Carbon in Two Created Wetlands

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Abbreviations: BD: bulk density; C: carbon; CCW: Charles City wetland; DBH: diameter at breast height; OC: organic carbon; OM: organic matter; WWE: Weanack wetland experiment

Abstract

Carbon (C) sequestration is an important wetland function, especially in forested wetlands that store C in woody biomass. Compost and topsoil amendments may help vegetation establishment in wetlands created to replace natural wetland loss, but long-term effects on mass C are not widely reported. The objective of this study was to estimate total mass C and determine long-term treatment effects of compost and topsoil in two reforested created wetlands- the Weanack Wetland Experiment (WWE; tidal, sandy, freshwater forested) and Charles City Wetland (CCW; clayey hardwood mineral flat). The wetland sites are located in the Virginia Coastal Plain. Bald cypress (*Taxodium distichum* [L.] Rich.) and other hardwoods were planted at WWE, and river birch and (*Betula nigra* L.) pin oak (*Quercus palustris* Muenchh.) were planted at CCW. Amendments at WWE were applied in 2003 and included wet compost at rates of 0, 78, and 156 Mg ha^{-1}, topsoil plus 78 Mg ha^{-1} compost, and topsoil only. Amendments at CCW were applied in 2002 and were dry compost rates at 0, 56, 112, 224, and 336 Mg ha^{-1}. At WWE, there were no treatment effects on mass C in root, litter, herbaceous, or woody fractions. Adding loamy topsoil to the sandy WWE wetland increased soil mass C after 12 years, but compost loading rates used had no effect on mass C over the control. At CCW, 14 years after compost treatment applications, there were loading rate effects on soil, root, and total mass C, but no long-term treatment effect on litter or woody fraction mass C. Compost treatments of 224 Mg ha^{-1} are the most beneficial to increasing long-term soil and root mass C in fine-textured, compacted wetlands like CCW, but there was little long-term advantage to adding a higher rate (336 Mg ha^{-1}). Overall, after 12-14 years, the addition of compost did not increase mass C in the tidally-influenced sandy created wetland but did increase mass C in the drier clayey mineral flat created wetland.

Introduction

Wetlands provide ecological functions such as carbon sequestration, sediment trapping, floodwater retention, groundwater recharge, water purification, nutrient sequestration and/or removal, and unique habitats for endangered species (Mitsch and Gosselink, 2007). Wetland ecosystems are among the most productive in the world, but not all wetlands perform the same functions, or perform functions equally well.

Ecosystems store organic carbon (OC) in nonliving forms such as soil organic matter (OM), litter, and dead plant tissue, and in living forms such as vegetation (e.g. herbaceous and woody) and the active microbial biomass. The sum of nonliving mass soil C, litter organic C, and living biomass mass C is the total mass C. In wetland ecosystems, the nonliving OC storage is higher than in other surrounding ecosystems and is considered an energy reserve for the ecosystem (Wetzel, 1992; Collins and Kuehl, 2001). In Virginia created wetlands and paired natural wetlands the soil mass C to 105 cm ranges from about 47 Mg C ha^{-1} to 176 Mg C ha^{-1} (Fajardo, 2006). However, there was carbonate C present for at least one of the sites that raised the total C values in the subsoil, so a representative high value in the range is closer to 91 Mg C ha^{-1} where carbonates are not present (Fajardo, 2006). On a global scale, there is more mass C stored in soils (1500-2400 Pg C) than in living biomass (450-650 Pg C) (Ciaiset al. 2013).

In wetland soils, the O horizons (if present) are composed of fresh litter to highly decomposed organic materials such as plant litter and debris such as dead stems and branches. The type and amount of litter in a wetland depends upon the vegetation present. In forested wetlands in the southern United States, annual litter fall accounts for approximately 50% of the net above-ground C accumulation (Mitsch and Gosselink, 2007). Litter accumulation and the resultant stable organic compounds such as humus may serve as a C sink in wetlands because the anaerobic conditions limit the decomposition of OM and the release of CO_2 gas (Reddy and DeLaune, 2008) via heterotrophic respiration.

Biomass C (Mg ha^{-1}) is the measure of C in living plant tissue, excluding litter and debris. Johnson and Rejmánková (2005) measured the C content in four wetlands in Belize, with the goal of determining whether agricultural practices were affecting adjacent wetland properties. The study wetlands had varying soil type (sandy to clayey) and herbaceous vegetation composition. The plant C varied by species; *Cladium* (a moss) had the highest plant C content, *Typha* had the next highest, and the *Eleocharis* species together had the lowest C content. The authors concluded that C content reflected the cellulose content of the species present (Johnson and Rejmánková, 2005), and that biomass C varies more with plant species than other environmental factors.

Mitsch et al. (2012) estimated that the world's wetlands may be net C sinks of 830 Tg $year^{-1}$ of C with a weighted average of 118 g C m^{-2} $year^{-1}$ of net C retention (Mitsch et al., 2012). The majority of the net C retention occurs in tropical and subtropical wetlands, due to their large global extent. Estimates of dry-weight biomass per unit area of land and their change over time can be used by land managers to estimate C pools and fluxes on individual properties, by policymakers to estimate forest C dynamics at large scales, and by scientists to improve our understanding of C dynamics and sequestration (Jenkins et al., 2004).

Increased greenhouse gasses in the atmosphere may lead to global climate change (Myhre et al., 2014). Soils generate, absorb and release these gasses through processes that include microbial decomposition and respiration. Processes that increase soil C storage can help mitigate climate change (Bliss et al., 2014). Elevated concentrations of greenhouse gasses released from wetland soils has led environmental scientists to realize the importance of properly managed soils as a significant terrestrial C sink (Minasny et al., 2014). Some scientists estimate that methane emissions from wetlands are approximately 115–227 Tg-CH_4 $year^{-1}$, which is 20–25% of current global methane emissions (Whalen 2005; Bergamaschi et al. 2007; Bloom et al. 2010). Mitsch et al. (2012) studied seven created and natural, temperate and tropical wetlands and constructed a model to simulate the net atmospheric radiative forcing (due to both CO_2 and methane fluxes) and C exchange of the studied wetlands. The model was then used on 14 other wetlands, including temperate, tropical, and boreal wetlands, to evaluate the net radiative forcing and C exchange on a global scale. Over a projected 300 years, C lost to methane emissions was estimated to be less than net C sequestration in these wetlands. They reported that when balancing greenhouse gas emissions and C sequestration, almost all wetlands are net sinks. Therefore, the creation or restoration of wetlands can be used to sequester C despite CO_2 and CH_4 emissions (Mitsch et al., 2012).

Houghton and Skole (1990) estimated the total C storage of wetland ecosystems on average to be 1,300 g C m^{-2} yr^{-1}, compared to 65 g C m^{-2} yr^{-1} in temperate forests, and 620-800 g C m^{-2} yr^{-1} in tropical forests. In general, wetlands that are closed systems, such as seasonally saturated wetlands, tend to have lower mass C than systems that have increased nutrient imports from surface and groundwater, such as tidal marshes (Sharitz and Pennings, 2006) or bottomland swamps.

Freshwater tidal wetlands are particularly sensitive to global climate change. The combination of upstream disturbance and sea level rise can lead to the salinification of surface and ground water in freshwater tidal wetlands (Perry and Atkinson, 2009; Middleton and Souter, 2016). This would negatively impact the many species in these ecosystems that are intolerant of salinity (Keddy, 2010).

It is important to ensure created wetlands successfully replace functions of natural wetlands, such as C sequestration. Amendments such as compost help establish created wetland vegetation and may be useful for increasing mass C over time. The objectives of this study are to determine long-term topsoil and compost amendment effects on mass C in soils and litter, and biomass C in above-ground biomass fractions at two created wetlands in Virginia.

Materials and Methods

Site Properties

Weanack Wetland Experiment (WWE)

The Weanack Wetland Experiment is a 2.74-ha created wetland located immediately south of Shirley Plantation on the James River floodplain in the Virginia Coastal Plain in Charles City County at 37.330922N, 77.265518W (Figure 5.1). Average annual total precipitation (almost all rainfall) is 109 cm, with about 61 cm of the total falling between April and September (Hodges and Thomas, 2005). The hydrology is tidally influenced with respect to daily groundwater fluctuations but inundation rarely occurs during the growing season. Some inundation occurs during the non-growing season, and the entire wetland occasionally floods up to 1 m deep during strong winter storms and fall hurricanes. The soils at the site are saturated within 15 cm of the surface most days of the year.

The pre-treatment soil formed in an artificial upland deposit of dredged sand from the James River which buried the native hydric soils by more than 3 m. The site was excavated and graded to a near level configuration in late 2003. The final design elevation of the experimental area discussed here is near sea level, ranging from 1.01 to 1.13 m above mean low tide in an adjacent (~ 50 m away) open water cove. The targeted vegetation was deciduous forest.

The experiment was established as a completely randomized design (Figure 5.2). There were five treatments with four replicates each, except the control, which had five replications (treatment 1 = control, treatment 2 = 78 Mg ha^{-1} compost, treatment 3 = 156 Mg ha^{-1} compost, treatment 4 = 15 cm topsoil plus 78 Mg ha^{-1} compost, treatment 5 = 15 cm topsoil only). The 78 and 156 Mg ha^{-1} rates of compost added approximately 5 and 10 Mg C ha^{-1}, respectively. Plots that received 15 cm of stockpiled topsoil from a nearby Pamunkey soil (Soil Survey Staff, 2014a) were undercut to a 15-cm depth beforehand to prevent differences in the average plot elevation after topsoil placement (Dickinson, 2007). The topsoil treatments were applied on October 22, 2003. Compost treatments were applied volumetrically based on a measured volume/weight ratio and are given in units of wet weight applied and were applied on October 27, 2003. The compost amendment was 50.4% solids with a C to N ratio of 20.6, and total OC content of 12.61% (Dickinson, 2007). All plots received the same fertilizer treatment of 280 kg ha^{-1} 10-10-10 (N - P_2O_5 - K_2O) fertilizer in October 2003. After topsoil and compost treatments were applied, the entire experimental area was chisel plowed to 15 cm on October 30, 2003. The topsoil amendment was dominantly loam Ap horizon removed from nearby gravel mined lands, although there was minor textural variation (Dickinson, 2007). The deeper (25 to 27 cm) samples taken in 2006 were all sand textured, with sand content ranging from 89-98%.

Each experimental unit contains one shallow excavated pit, with an original diameter of approximately 0.75 m and 20 cm deep, and an adjacent 0.75 m diameter mound of soil excavated from the pit to simulate treefall microtopography. Pits and mounds were installed in March, 2004. Also, in March, 2004, one bald cypress (*Taxodium distichum* [L.] Rich.) was planted in each pit, one on each mound, and one or more on level ground in each experimental unit (Dickinson, 2007; Pietrzykowski et al., 2015). A mix of second-year tubeling trees were planted on April 23-26, 2004 at an average density of 1,086 trees ha $^{-1}$(Dickinson, 2007). Trees planted included willow oak (*Quercus phellos* L.), sycamore (*Platanus occidentalis* L) green ash (*Fraxinus pennsylvanica* Marsh.), hazel alder (*Alnus serrulata* [Ait.] Willd.), and bald cypress. An herbaceous seed mix was applied on May 10-14, 2004 to the entire experiment site after soil amendments were added. The seed mix contained spotted ladysthumb (Polygonum *persicaria* L.), Pennsylvannia smartweed (*Polygonum pensylvanicum* L.), arrowleaf tearthumb (*Polygonum sagittatum* L.), rice cutgrass (*Leersia oryzoides* L.), fringed sedge (*Carex crinita* Lam.), and redtop panicgrass (*Panicum rigidulum* Bosc ex Nees) (Dickinson, 2007).

By spring 2005, the hydrology of the site met the U.S. Army Corps of Engineers (COE) and Virginia Department of Environmental Quality (VA DEQ) criteria for wetland hydrology. This determination was confirmed by well readings that indicated the freshwater forested wetland was hydrologically-connected to the tidal cycle of the James River (Vanasse Hangen Brustlin, 2005), mainly through a cyclic pulse of groundwater through its very sandy substrate.

Charles City Wetland (CCW)

The Charles City Wetland (CCW) is located on the Claddagh Farm in Charles City County, Virginia. The overall created wetland site around the experiment is approximately 19.3 ha. This wetland was initially created in 1996 to compensate for forested wetland loss due to road construction by VDOT. At CCW there are two separate created wetland experiments that are labeled CCW-Dry at 37.343902N, 76.926898W and CCW-Wet at 37.343569N, -76.926034W (Figure 5.1). When the wetland was first constructed in 1996, about 45-60 cm of surface soils (O + A + E horizon) were removed, which left a silty lower E or clayey Bt or Btg horizon exposed at the surface over most of the site. The upper part of this soil became extremely compacted and dense due to the use of heavy machinery during construction of the wetland (Bergschneider, 2005).

The two experiments at CCW were separated based on differing hydrophytic vegetation and hydrology in 2002. The CCW-Dry experiment did not meet wetland vegetation criteria and was dominated by sericea lespedeza (*Lespedeza cuneata* [Dum. Cours.] G. Don) and beaked panicgrass (*Panicum anceps* Michx). The CCW-Wet experiment was dominated by hydrophytic vegetation (*Typha latifolia* L., *Scripus* spp., *Carex* spp.). The CCW-Dry experiment is set up as a completely randomized design (CRD), and the CCW-Wet experiment is set up as a randomized complete block design (RCBD). The CCW-Wet experiment was split into four blocks along the very slight local (< 1%) contour and the blocks were separated to adjust for local differences in site wetness (Figure 5.2). Each experiment has 20 plots, each 4.6-m by 3.0-m, and the plots are separated by 3-m alleyways. Each experiment has four adjacent 'pseudo-control' plots (i.e., untreated except for the planting of trees) that represent the experimental soils prior to manipulation (Bergschneider, 2005).

The OM amendment applied in July 2002 was a mixed wood and yard-waste compost produced by Grindall Inc. of Richmond. There were five different treatment levels (treatment 1 = 0 Mg ha^{-1}, treatment 2 = 56 Mg ha^{-1}, treatment 3 = 112 Mg ha^{-1}, treatment 4 = 224 Mg ha^{-1}, and treatment 5 = 336

Mg ha^{-1} compost added on a dry weight basis), with four replicates per treatment in each experiment (Figure 5.2). These compost loading rates added approximately 9, 18, 36, and 54 Mg C ha^{-1}, respectively. The yard-waste compost could not be fully incorporated into the mineral soil surface in treatments 4 and 5 because of the thickness of the organic amendment on first conventional disking effort, so further incorporation was accomplished using a garden tiller. The high rates of compost in treatments 4 and 5 made the original pre-seeding surface elevation 10 to 15 cm higher than the other treatments (Bergschneider, 2005). However, the difference in surface height between plots due to compost thickness is no longer noticeable.

In December 2002, five pin oak (*Quercus palustris* Muenchh.) and five river birch (*Betula nigra* L.) seedlings were planted in each plot. The pin oaks were planted in a star pattern in one half of the plot, and the river birches in a star pattern in the other half. A limited number of trees were damaged by rodents and deer during the first winter and were replaced in March and May of 2003. Herbaceous species were not seeded, but seeds from the pre-existing cover germinated and covered over 90% of the plots by mid-summer of 2003.

Sampling

Bulk density (BD) and OC content were used to determine soil mass C. There are no carbonates at either wetland, so total C (TC) is the same as OC. At WWE, three BD samples were taken by horizon to 30 cm using a BD hammer and the volumetric core method 3B6a (Soil Survey Staff, 2014b). There were two to four horizons per plot at WWE. At CCW, two BD samples were taken by horizon to 30 cm using a BD hammer and the volumetric core method 3B6a (Soil Survey Staff, 2014b). Ap horizons at the surface were sampled twice if depth was > 8 cm (one sample at 0-5 cm, one sample from the bottom 2.5 cm of the Ap) to account for a possible lower BD or higher OC at the surface compared to the bottom of the Ap. Soils below 30 cm depth had an average of less than 0.5% OC, so only soils in the upper 30 cm were used to find total soil mass C (Table 5.1). After BD calculations (including rock inclusion weight and volume), the samples were combined for TC analysis using an Elementar CN analyzer (Elementar Americas Inc., Mt. Laurel, NJ).

Three litter samples were collected per plot at WWE in August, 2016 and in September, 2016 at CCW. Fibric (Oi) and hemic (Oe) horizons were included in the litter analysis. No Oa horizons were found. All litter samples were in collected in 50 by 50 cm quadrats, placed in paper bags, transported to Virginia Tech, dried in ovens at 65°C and weighed (McKee et al., 2013; Wang et al., 2013). Sample weights were scaled up to Mg ha^{-1} using plot size, and mass C was estimated by multiplying 65°C oven-dry litter mass by 0.5.

Four root samples to 30 cm were taken per plot at WWE in 2015. Three root samples were collected in each plot at CCW. Replicates were located either between pin oaks, between river birch, or at plot center to ensure that tree type did not have an effect on root mass. Root samples were taken to 30cm. All root samples were transported to the lab in coolers and stored in a refrigerator, then gently washed in sieves. Roots were then dried in an oven at 65°C (Böhm, 1979; McKee et al., 2013). Mass C was found by multiplying oven-dry root mass by 0.5 (Cook et al, 2014).

Herbaceous biomass was sampled at WWE in August, 2016. There were three samples per plot taken from 50 by 50 cm quadrats, transported back to the lab in coolers, separated by vegetation type (forbs, grass, vines, woody), and dried in ovens at 65°C (McKee et al., 2013; Wang et al., 2013). Woody vegetation included tree seedlings < 50 cm tall.

Height and diameter at breast height (DBH) of trees were measured. Bald cypress trees were measured at WWE, and pin oak and river birch trees were measured at CCW. A Philadelphia style telescoping measuring pole was used to measure height in meters (Curtis and Bruce, 1968), and a diameter tape was used to measure DBH (1.3 m above ground) in inches. A preliminary plot inventory in the summer of 2014 showed a high density of trees, particularly black willow (*Salix nigra* Marshall) and red maple (*Acer rubrum* L.). Many of these trees were taller than 50 cm and were not included in clip plots and were not sampled as a sapling stratum due to time constraints. Table 5.2 includes a tree counts from three plots at WWE in 2014.

Analysis

Equation 1 was used to determine mass C per horizon (Bliss and Maursetter, 2010). The mass C was summed for the upper 30. A t-test was used to determine whether Ap1 (0-5 cm) and Ap2 (~ 6-8.5 cm) horizons at CCW had similar mass C to pool the data into an Ap horizon group. Mass soil C was analyzed by horizon.

$$C_h = C_O D_{bw} ML * 100 \quad \text{(Eq. 1)}$$

Where C_h represents mass soil OC in a 1-ha area of each soil horizon (Mg C ha^{-1}); C_O is the soil OC percentage divided by 100 (kg kg^{-1}); D_{bw} (g cm^{-3}) is the soil BD (g cm^{-3}); M (kg kg^{-1}) is the percentage by weight of the < 2-mm soil fraction/100, L is the horizon thickness (cm), and 100 is used to convert units from g cm^{-2} to Mg ha^{-1}.

Allometric equations were used to estimate woody biomass (lbs) based on DBH (inches) for trees at both sites (Table 5.3). Biomass estimates were converted to kg for statistical analysis. Equations were selected based on region (Southeast United States), and tree size. A geometric mean was used to find DBH of trees with more than one stem. When measuring trees that buttress in wetlands (e.g. bald cypress) to predict volume, it may be more accurate to use a diameter at 10 ft rather than at DBH (Parresol et al., 1986; Parresol and Hotvedt, 1990). However, we measured DBH and height of cypress trees in 2015 because biomass equations usually use one or both of those measurements. An equation for green weight biomass of bald cypress was used (Swindel et al., 1982), and was converted to oven dry biomass using an average moisture content of 95% (oven-dry weight basis) (Wenger, 1984; Miles and Smith, 2009). Biomass C of the trees was estimated by multiplying estimated biomass by 0.5 (Cook et al, 2014).

At both WWE and CCW, the tree biomass C per species was summed and converted to Mg ha^{-1} based on plot size to use for total mass C calculation. At WWE, Equation 2 was used to estimate total plot mass C. At CCW, invader trees such as sycamore were also measured and their biomass was calculated using equations from Clark et al. (1985), but they were not included in plot mass C totals. Invader trees were not included in plot mass C totals so that possible treatment effects could be tested. Total mass C at CCW was calculated using Equation 3.

$$C_T = C_S + C_L + C_R + C_H + (C_B * 10 * A^{-1}) \quad \text{(Eq. 2)}$$

Where C_T represents the total mass C in a plot (Mg C ha^{-1}); C_S represents the sum of soil mass C by horizon to 30 cm (Mg C ha^{-1}); C_L is the mean mass C in litter per plot (Mg C ha^{-1}); C_R is the mean root biomass C per plot (Mg C ha^{-1}); C_H is the mean herbaceous biomass per plot (Mg C ha^{-1}); C_B is the total kg of cypress biomass C in each plot (kg); and A is the plot area (m^2).

$$C_T = C_S + C_L + C_R + (C_{rb} * 10 * A^{-1}) + (C_{po} * 10 * A^{-1}) \quad \text{(Eq. 3)}$$

Where C_T represents the total mass C in a plot (Mg C ha^{-1}); C_S represents the sum of soil mass C by horizon to 30 cm (Mg C ha^{-1}); C_L is the mean mass C in litter per plot (Mg C ha^{-1}); C_R is the mean root biomass C per plot (Mg C ha^{-1}); C_H is the mean herbaceous biomass per plot (Mg C ha^{-1}); C_{rb} is the total kg of river birch biomass C in each plot (kg); C_{po} is the total kg of pin oak biomass C in each plot (kg); and A is the plot area (m^2).

A regression model was used for each level of biomass (soil, root, litter, herbaceous, woody), with compost loading rate as the predictor and mass C as the response. Regression assumptions were checked by visual tests (i.e. plotting predicted vs residual), and a Box-Cox transformation was used when assumptions were not met. For tree data, plot 2 at CCW-Dry was omitted because it had no surviving trees. The lack of trees was due to herbivory rather than any compost treatment effects. A multiple linear regression allowed for testing multiple variables at once (i.e. compost loading rate and tree survival) for effects on mass C. A significance level of α=0.05 was used for all statistical tests.

Results and Discussion

WWE

Soil mass C to 30 cm at WWE varied with treatment (p=0.0129) (Table 5.4). Plots with loamy topsoil had higher mass C than plots in the control (41.28 and 32.32 Mg ha^{-1} in treatments 4 and 5 vs 20.24 Mg ha^{-1} in the control). The fine texture of the loamy topsoil retained more mass C in the upper 30 cm compared to the sandy treatment plots. Compost did not have an effect on total soil mass C in the sandy or loamy soils. It is possible that higher rates of compost (> 178 Mg ha^{-1}) would cause long-term effects on mass C at WWE, but these higher rates may not be feasible to apply. In a tupelo-cypress wetland studied by McKee et al. (2013), the soil mass C comprised a majority (50-66%) of the total C at the site. This is in contrast to the results at WWE where soil mass C made up about 22-39% of total C.

During soil description sampling it was noted that there were very few roots below 25-30 cm in most plots. There were three root samples that contained pieces of large woody cypress root and had a larger sample weight than the rest of the data set. These three samples were considered "outliers" and excluded from the root C analysis. With these samples removed, there was a compost effect on root biomass, with treatments 3 (156 Mg ha^{-1} compost) and 4 (topsoil plus 78 Mg ha^{-1} compost) having higher root mass C than treatments 1, 2, and 5 (p=0.0581).

Litter weights at WWE did not vary by treatment after 12 years (p=0.0908) (Table 5.4). This may be attributed to a lack of differences detected in the other biomass parameters that were measured (cypress, forbs, vines). Cypress trees contribute to a large amount of the litter at WWE, so a lack of growth difference between cypress trees led to similar litter amounts across the site.

Total herbaceous biomass at WWE did not vary by treatment (p=0.2134) (Table 5.4). Total herbaceous biomass comprised an average of 0.3-0.7% of the total C at WWE, which is consistent with results in a tupelo-cypress wetland studied by McKee et al. (2013) where the herbaceous understory comprised only approximately 1.0% of the total C at the site. There was greater biomass C of grasses in treatments 5 and 4 than in treatments 1 and 3 (p=0.0011) (Figure 5.3). Plots in treatment 1 had greater woody sapling biomass C than in the rest of the treatments (p=0.0399). Biomass C of vines and forbs did not vary by treatment. A 50:20 dominance test in 2016 showed that all plots at WWE met COE criteria for hydrophytic vegetation (Table 5.5) (U.S. COE, 2010). The herbaceous biomass and population likely differed across the wetland due to a slight hydrologic variance (by observation, no recent measured well data). Treatments 5 and 4 produced more grass biomass, while treatment 1 produced more woody sapling biomass. The higher grass biomass in the topsoil treatments may be due to an upland seedbank in the topsoil. Dickinson (2007) reported that two and three years after treatment application, plots in topsoil treatments had more upland species and fewer obligate wetland species than plots in the control due to having an upland seedbank. Overall there were many factors that influenced the herbaceous biomass at WWE over time.

Cypress height and DBH did not vary by treatment at WWE (p=0.9873; 0.8634). The cypress biomass equation used to estimate biomass C included DBH, so mass C accordingly did not vary by treatment (p=0.8186). Pietrzykowski et al. (2015) also found that cypress growth was not affected by soil treatment and noted that competition from other woody tree and shrub species may negatively affect cypress growth. At WWE, the mean density of planted and invader woody species per plot ranged from 15.8 stems/plot to 31.5 stems/plot, and was not affected by treatment (Pietrzykowski et al., 2015).

The total mass C did not vary by treatment at WWE ($p=0.8767$) (Table 5.4). The mean total mass C at WWE ranged from 79.0 to 105.5 Mg C ha^{-1} and did not vary significantly by treatment. Only one of the components of total mass C (soil C to 30 cm) varied by treatment, so logically, the total would only vary if the soil C was a larger proportion of the total (Figure 5.4). The mean soil mass C to 30 cm at WWE ranged from 20.24 to 41.28 Mg ha^{-1}, which is similar to a previously estimated soil mass C to 45 cm in Virginia created wetlands (35 Mg C ha^{-1} to 80 Mg C ha^{-1}) reported by Fajardo (2006). These results underestimate total mass C at WWE because trees other than bald cypress were not included in biomass estimates unless they were < 50 tall. There were no compost treatment effects found on cypress growth reported in this study or by Pietrzkowski et al. (2015).

CCW

At CCW-Dry and CCW-Wet, soil mass C in the upper 30 cm varied by treatment ($p<0.0001$; $p<0.0001$). There was one "outlier" point removed from the data, which was plot 13 at CCW-Wet. Plot 13 was described and sampled as an Ap1, Ap2, BA, and Btg horizon. The BA horizon had higher mass C than the Ap1 or Ap2 horizons because it had a higher BD (1.29 g cm^{-3} compared to 0.81 g cm^{-3} and 0.80 g cm^{-3}) and horizon thickness (14 cm compared to 5 and 6 cm) even though it had a lower OC content (2.53% compared to 6.56% and 6.41%). After the outlier was removed, a regression model was fit to the data (Table 5.6). A linear regression with the outlier removed had a higher R^2 and lower RMSE than a regression line with the outlier (R^2 =0.774517, RMSE=10.29162 with outlier). Regression equations for total soil mass C summed to 30 cm are in Table 5.6 (CCW-Dry) and Table 5.7 (CCW-Wet).

There was a long-term effect of compost loading rate on soil mass C in the upper 30 cm of CCW-Dry and CCW-Wet. Visual observations showed that almost all recognizable compost fragments have decomposed in the 14 years after application. As the compost decomposed, organisms (and the plowing) have mixed the compost throughout the upper ~25cm of soil (Ap and BA horizons). We occasionally observed large woody debris laying along the upper contact with the Btg horizons at the base of the presumed original plowing depth. The BA horizons had a higher BD and sometimes greater thickness than the Ap horizons (which have decreased in thickness over time as the OM decomposed).

There was no compost effect on root mass at CCW-Dry (p=0.0593, R^2 = 0.06099). Two variables for tree survival per plot (river birch count, pin oak count) were added to the regression model but did not improve the model (p=0.2540; p=0.5215). At CCW-Wet, compost loading rate was a significant predictor of root mass (p<0.0001) and explained about 33% of the variability in root mass (R^2=0.3320403) (Table 5.6). Plant roots were not identified after collection, but the majority of plant roots collected appeared to be very fine to medium sized, and likely belonged to herbaceous plants. Sampling location did not affect root biomass at either wetland (p=0.7060; p=0.3187).

There was a long-term effect of increased root proliferation with compost at CCW-Wet, but not at CCW-Dry. Root mass did not vary by sampling location within plots, possibly because care was taken to sample at least 30 cm from trees. Root mass C may have been underestimated at both sites because heavy coarse tree roots were not found in the samples. Herbaceous ground cover was sparse in the heavily shaded plots, so root weights were mostly low. Herbaceous ground cover was sparse in the heavily shaded plots, so root weights were mostly low.

At CCW-Dry, plot 5 (treatment 1) was removed as an unexplained outlier for analysis of litter biomass at CCW-Dry. Plot 2 was also removed as it did not have any surviving trees. After removing these data from the litter mass C data set, the total tree count did not have an effect on litter C (p=0.13929). Excluding plot 2, compost loading rate did not have an effect on litter amounts (p=0.8004), and the amount of pin oaks also did not have an effect on litter C per plot (p=0.7366). A Kruskal-Wallis test showed that river birch count did have an effect on litter C at CCW-Dry (p=0.0117). Plots with four or five surviving river birch trees had more litter C than plots with three surviving river birches. Number of pin oak trees likely did not affect litter C because the differences in pin oak heights and biomass differed, which would confound litter treatment affects. Number of river birch did affect the amount of litter C because river birch trees were more consistent in size (height and DBH did not vary by treatment).

Litter mass C at CCW-Wet did not vary with compost rate, even after a transformation to correct regression assumption violations (p = 0.1083, R^2 = 0. 043867). A regression model with compost and tree counts as variables also did not predict litter biomass C (p=0.1564, adj. R^2 = 0.047197). Tree counts of pin oak, river birch, and 'other' trees were added to the regression model but did not improve the adjusted R^2 value of the model compared to a linear regression model with compost loading rate as the only predictor.

Pin oak height varied by treatment at CCW-Dry (p=0.0009). Trees in treatment 4 were taller than trees in the rest of the treatments (Table 5.8). Pin oak DBH varied by treatment at CCW-Dry (p=0.0001). Pin oaks in treatments 4 and 5 had larger DBH than those in treatments 2 and 3. Accordingly, pin oak biomass was affected by compost loading rate (p=0.0001). Pin oak mass C has a general trend of increasing with compost loading rate at CCW-Dry, except for treatment 3, which was lower than treatment 2. Pin oak biomass did not have a linear relationship with compost loading rate, so and ANOVA was used instead of a regression. Bergschneider (2005) found that one year after planting, pin oak growth increased with compost loading rate up to 224 Mg ha^{-1}. Compost likely increased initial pin oak growth due to increased nutrient content, soil water holding capacity, lower BD, and increased rooting volume. In 2016, the lasting effects of compost on soil properties (decrease in BD, increase in some soil nutrients) produced benefits for long-term pin oak growth at CCW-Dry. There were several pin oak seedlings in the experiment plots, which indicates that the wetland is going through primary succession.

Pin oak height varied by treatment (p=0.0272) at CCW-Wet, where pin oaks in treatments 3 and 4 were taller than those in treatment 2 (Table 5.8). Pin oak DBH did not vary by treatment (p=0.1141). One pin oak at CCW-Wet was found to be an outlier in total mass C. This tree was in treatment 5 and had a height of 7.35 m, with two trunks 4.5 and 4 inches DBH. This tree appeared to be two separate pin oaks that grew together, which made it much larger than the other pin oaks. This tree was removed for regression analysis. After removal of the outlier tree and a Box-Cox transformation, a regression was fitted to the transformed data, compost was not a significant predictor for pin oak biomass C (p=0.3803). Mass C is estimated from biomass equations that use DBH rather than height, so mass C in pin oaks accordingly varied by treatment. The wetter conditions at CCW-Wet compared to CCW-Dry may have stressed pin oak growth in combination with the high BD of the Bt horizons, which limited the positive response to compost additions.

Neither river birch height nor DBH varied by treatment at CCW-Dry (p=0.2857; 0.3082) (Table 5.9). There was no relationship between compost rate and river birch biomass at CCW-Dry (p=0.3259). As with pin oak mass C, river birch mass C did not consistently increase with loading rate, so an ANOVA was used to determine significance rather than a regression. River birch height and average DBH at CCW-Wet did not vary by treatment (p=0.6723; p=0.2771) (Table 5.9). There were two river birch trees at CCW-Wet that were outliers in total mass C. These two trees were much higher in biomass C than other river birch, were located in plots 13 (treatment 4) and 20 (treatment 5), had a height of 8.65 and 9.27m, and average DBH of 7.78 and 8.32 inches. River birch biomass was not affected by compost loading rate in a linear regression (R^2 = 0.041779). Overall at CCW-Wet, river birch growth parameters (height, DBH, biomass C) were unaffected by compost loading rate, so biomass C accordingly was similar across treatments. These results are in contrast to Bergschneider's (2005) finding that river birch growth increased with compost loading rate one year after planting. Compost amendments originally led to a large difference in soil properties (OC, BD, plant available nutrients) between treatments soon after application, but over time these differences have diminished. Plant growth difference between treatments will accordingly diminish over time as BD decreases in treatments 1-3 and increases in treatments 4 and 5.

For CCW-Dry total mass C analysis, plot 2 was excluded because it had no surviving river birch or pin oaks, which caused it to be an outlier. This plot has a total mass C of much less than the other plots; it had 74.59 Mg C ha^{-1} compared to an average of 180.26 Mg C ha^{-1} in the remaining plots at CCW-Dry. Overall total mass C in CCW-Dry varied with compost loading rate ($p<0.0001$). A linear model fit the data better than a quadratic model, however a Tukey's HSD test showed there was no difference between total mass C in treatments 4 and 5 ($p=0.9994$). Compost was also a significant predictor for total mass C at CCW-Wet ($p<0.0001$). Biomass of additional trees per plot is presented in table 5.10 but was not included in the total mass C estimates.

Long-term total mass C at CCW was affected by compost loading rate (Figure 5.5). After 13 years, there was no advantage on total mass C from the higher loading rate above 224 Mg ha^{-1}. Most of the mass C at CCW is stored in the top 30 cm of soil and in living trees. Average total mass C ranged from 144.9 Mg ha^{-1} (treatment 1) to 217.8 Mg ha^{-1} (treatment 5) at CCW-Dry, and from 103.0 Mg ha^{-1} (treatment 1) to 186.3 Mg ha^{-1} (treatment 5) at CCW-Wet.

Conclusions

Compost additions may increase soil mass C in created wetlands. Fine-textured soils (e.g. loamy topsoil at WWE, BA horizons at CCW) increased mass soil C. Root biomass was affected by compost at WWE but not at CCW, and litter was unaffected at both sites. Herbaceous biomass at WWE was affected by treatment, but some herbaceous strata was dominated by upland invader species and so higher herbaceous biomass in the topsoil plots may not be a positive effect. Herbaceous biomass only comprised a small portion of the total mass C at WWE, while most mass C was in soil and woody biomass. No long-term compost effects were seen on growth or biomass of cypress or river birch. Pin oak biomass was highest in plots with 224 Mg ha^{-1} applied at CCW-Dry but was unaffected by treatment at CCW-Wet. However, these trees did contribute to a large portion of the total mass C in each wetland.

We recommend adding compost during wetland creation to raise long-term soil mass C and total mass C. Ideal compost loading rate varies with wetland type (texture, BD, hydrology) and mitigation goals.

In the types of wetlands studied here, a rate near 224 Mg ha^{-1} may be ideal for treatment effects that last for more than 13 years compared to an unamended control. If mitigation goals are only the immediate establishment of wetland vegetation and hydric soil properties, rates near 112-180 Mg ha^{-1} compost are recommended to stimulate early vegetation growth in the system (Bergschneider, 2005; Bailey et al., 2007; Bruland et al., 2009).

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Tables and Figures

Table 5.1. Soil bulk density and carbon data for soils below 30 cm at CCW. Samples were taken in alleys to minimize disturbance in plots. Btg1 horizons began in the upper 30 cm of soil plots.

Alley Location	Horizon	Lower Boundary	w	BD	Nitrogen	Carbon	C:N	Mass C (30-100 cm)
		cm	$g\ g^{-1}$	$g\ cm^{-3}$	------------ %	------------		$Mg\ ha^{-1}$
				--CCW-Dry --				
4+5	Btg1	92	0.06	1.69	0.04	0.23	5.69	25.76
4+5	Btg2	112	0.15	2.00	0.04	0.13	3.61	
4+5	Btg3	157	0.05	1.84	0.03	0.09	3.59	
4+5	BCtg	175	0.22	2.24	0.03	0.11	4.32	
4+5	Cg	190	0.03	1.06	0.03	0.10	3.62	
17+12	Btg1	65	0.12	1.60	0.05	0.36	6.89	30.63
17+12	Btg2	100	0.22	1.63	0.04	0.19	5.27	
17+12	Btg3	135	0.02	1.76	0.02	0.11	4.51	
17+12	BCtg	180	0.21	2.00	0.03	0.11	4.21	
17+12	Cg	190	0.23	1.69	0.03	0.14	4.75	
				-- CCW-Wet --				
3 + 8	Btg1	49	0.22	1.67	0.04	0.16	3.67	15.21
3 + 8	Btg2	82	0.17	1.89	0.03	0.10	3.90	
3 + 8	Btg3	106	0.19	2.12	0.02	0.09	3.79	
3 + 8	Btg4	160	0.21	1.68	0.02	0.14	7.65	
3 + 8	BCg	183	0.22	1.81	0.04	0.20	5.00	
12 +17	Btg1	44	0.20	1.60	0.04	0.15	3.96	16.07
12 +17	Btg2	97	0.18	1.84	0.03	0.12	3.94	
12 +17	Btg3	125	0.18	2.08	0.03	0.12	4.85	
12 +17	BCtg	155	0.22	1.87	0.03	0.17	5.25	
12 +17	Cg	190	0.22	1.49	0.03	0.15	5.30	

Table 5.2. Example tree count and estimated diamters in three plots at WWE in July, 2014.

Treatment	Plot	Tree	n	Diameter range
				inches
Control	7	Green ash	4	< 1
		Black willow	34	< 1.5
		Red maple	50	< 2
		Red elm	27	< 1
		Willow oak	1	
78 Mg ha^{-1} Compost	14	Black willow	19	.5 – 1.5
		Cottonwood	1	
		Red maple	25	.5 – 2.5
		Red elm	4	.5 – 2.75
156 Mg ha^{-1} Compost	21	Black willow	18	.5 – 3.5
		Red Maple	12	< 1
		Red elm	2	< 1

Table 5.3. Equations used to estimate woody biomass of three tree species at WWE and CCW.

Tree	Specifications	Equation	Reference
Bald Cypress	n/a	$W = -22.183 + 6.909 * D_i{}^2$	Swindel et al., 2018
River birch	DBH < 7.4 cm	$Y = 0.0787 * D^{2.7725}$	Brantley et al., 2016
River birch	DBH ≥ 7.4 cm	$Y = e^{-1.9123+2.3651\ln(D)}$	Jenkins et al., 2003
Pin Oak	DBH < 7 cm	$Y = 0.21345 * D^{2.2166}$	Brantley et al., 2016
Pin Oak	DBH ≥ 7 cm	$Y = e^{-2.0127+2.4342\ln(D)}$	Jenkins et al., 2003

W = aboveground green weight biomass (lbs)
D_i = DBH (diameter at breast height in inches)
Y = aboveground dry biomass (kg)
D = DBH (cm)

Table 5.4. Mean mass C by treatment and mass C strata at WWE. Within each column, numbers followed by different letters are significantly different (α = 0.05), with “ns” meaning no significant differences between means.

Treatment*	Compost C	Cypress Mass C	Soil C	Root C	Herbaceous C	Litter C	Total Mass C
	Mg ha^{-1}	--- kg ---	--------------------------------Mg ha^{-1}--------------------------------				
Control	0	65.36	20.24b	0.54	0.46	1.39	79.00
C78	4.96	84.44	23.74ab	0.69	0.34	1.49	94.23
C156	9.91	77.84	21.25ab	0.76	0.33	1.15	96.80
TS+C78	4.96	76.59	41.28a	0.77	0.54	1.03	105.46
TS	0	72.36	32.32a	0.69	0.67	1.61	98.64

* Treatment symbols: C78 = compost at 78 Mg ha^{-1}; C156 = compost at 156 Mg ha^{-1}; TS+C78 = topsoil plus 78 Mg ha^{-1} compost; TS = topsoil only.

Table 5.5. Percent of dominant wetland species by strata at WWE. A COE 50/20 dominance test was used. Data collected by Sara Klopf on August 16-17, 2016.

Treatment	Plot	Sapling	Shrub	Herbaceous	Overall	Hydrophytic? (Y/N)
		----------------------	%	----------------------		
Control	5	100	100	75.0	85.7	Y
	7	100	100	66.7	87.5	Y
	9	100	100	55.6	66.7	Y
	17	100	100	0.0	75.0	Y
	20	100	100	50.0	70.0	Y
78 Mg ha^{-1} compost	3	100	100	100.0	100.0	Y
	11	100	100	100.0	100.0	Y
	14	100	100	0.0	75.0	Y
	16	50	50	60.0	55.6	Y
156 Mg ha^{-1} compost	1	100	100	100.0	100.0	Y
	6	100	100	50.0	72.7	Y
	10	100	100	20.0	55.6	Y
	21	100	100	0.0	60.0	Y
Topsoil + 78 Mg ha^{-1} compost	2	100	100	85.7	90.0	Y
	12	100	100	50.0	83.3	Y
	15	100	100	80.0	90.0	Y
	18	100	100	50.0	83.3	Y
Topsoil only	4	100	100	33.3	66.7	Y
	8	100	100	75.0	85.7	Y
	13	100	100	66.7	83.3	Y
	19	100	100	50.0	85.7	Y

Table 5.6. Regression equations to estimate mass carbon after 13 years at CCW-Dry, based on compost loading rate. RMSE= root mean square error. Equations were chosen to lower RMSE and raise R^2 (or adjusted R^2 if there was more than one predictor).

Component	Equation	RMSE	R^2
Soil	$C_{s30} = 49.422893 + 0.1647661 * L$	13.30071	0.719778
Total	$C_T = 146.03048497 + 0.241979053 * L$	23.331079	0.6429228

L = compost loading rate (Mg ha^{-1})
T = number of trees in a plot
C_{s30} = Soil mass C to 30cm (Mg ha^{-1})
C_r = root biomass carbon (Mg ha^{-1})
C_L = litter mass C (Mg ha^{-1})
C_T = total mass C across sampled strata (soil, roots, litter, trees) (Mg ha^{-1})

Table 5.7. Regression equations to estimate mass carbon after 13 years at CCW-Wet, based on compost loading rate. RMSE= root mean square error. Equations were chosen to lower RMSE and raise R^2 (or adjusted R^2 if there was more than one predictor).

Component	Equation	RMSE	R^2
Soil	$C_{s30} = 40.304289 + 0.1404172 * L$	6.5486612	0.8850002
Roots	$\frac{{C_r}^{0.234} - 1}{0.438290936} = -0.624911 + 0.0018537 * L$	0.3212692	0.3320403
Total	$C_T = 100.82594651 + 0.2888091009 * L$	25.09129	0.681735

L = compost loading rate (Mg ha^{-1})
C_{s30} = Soil mass C to 30cm (Mg ha^{-1})
C_r = root biomass carbon (Mg ha^{-1})
C_T = total mass C across sampled strata (soil, roots, litter, trees) (Mg ha^{-1})

Table 5.8. Pin oak measurements (height, diameter at breast height, and average biomass C per tree) in 2016 at CCW. Within each column under each site, numbers followed by different letters are significantly different (α = 0.05).

Compost	n	Height	DBH	Mass C
Mg ha^{-1}		m	cm	kg
		------------------ CCW-Dry ------------------		
0	19	5.36c	5.57b	6.44b
56	17	6.52bc	6.45ab	7.37ab
112	18	6.32bc	5.49b	5.34b
224	11	8.34a	8.81a	15.44a
336	16	7.27b	8.33a	12.91a
		----------------- CCW-Wet -----------------		
0	10	4.30ab	4.56	3.82
56	13	3.16b	3.34	1.95
112	14	4.72a	5.54	5.76
224	16	4.54a	5.07	5.49
336	16	4.36ab	4.74	3.94

Table 5.9. River Birch measurements (height, diameter at breast height, and average biomass C per tree) in 2016 at CCW. No significant differences between means by site were found.

Compost	n	Height	DBH	Mass C
Mg ha^{-1}		m	cm	kg
		------------------ CCW-Dry ------------------		
0	19	8.72	10.80	21.80
56	20	8.44	9.95	18.89
112	18	8.34	11.00	24.15
224	13	8.25	10.30	24.72
336	15	9.10	12.20	28.42
		----------------- CCW-Wet -----------------		
0	19	6.85	9.03	15.30
56	19	6.91	9.25	16.26
112	17	6.89	9.55	16.60
224	17	7.16	10.70	23.07
336	16	7.43	10.70	24.16

Table 5.10. Estimated biomass of invader trees at CCW.

Compost	Plot	Species	Height	mean DBH	Biomass	Mass C
Mg ha^{-1}			m	cm	kg	Mg ha^{-1}
		------------------------------ CCW-Dry ------------------------------				
56	10	Red Maple	6.10	3.81	13.87	5.03
56	14	Sweetgum	6.90	5.33	29.12	10.55
56	14	Sweetgum	8.38	8.64	91.12	33.01
56	18	Red Maple	2.85	1.27	0.72	0.26
112	19	Red Maple	2.98	1.02	0.48	0.17
112	19	Red Maple	2.37	1.27	0.60	0.22
112	19	Red Maple	3.49	2.54	3.53	1.28
112	19	Sweetgum	8.98	10.54	144.57	52.38
		------------------------------ CCW-Wet ------------------------------				
336	2	Red maple	3.43	1.27	0.87	0.31
336	2	Red maple	4.97	3.05	7.23	2.62
336	2	Sycamore	7.06	8.89	532.91	193.09
224	5	Red maple	4.35	3.59	8.79	3.19
224	5	Red maple	9.14	9.40	126.45	45.82
224	6	Red maple	2.60	0.76	0.24	0.09
224	6	Red maple	3.38	1.52	1.23	0.45
224	6	Red maple	2.60	2.41	2.37	0.86
112	8	Red maple	2.48	0.76	0.23	0.08
336	10	Red maple	9.20	11.27	183.16	66.36
336	11	Sweetgum	4.97	6.35	197.50	71.56
112	15	Black willow	7.50	16.40	1916.54	694.40
0	16	Black willow	3.74	2.54	24.39	8.84
0	16	Black willow	7.68	10.16	751.51	272.28
224	17	Red maple	5.10	2.79	6.24	2.26

* Equations used to calculate biomass were taken from Clark et al., 1985.

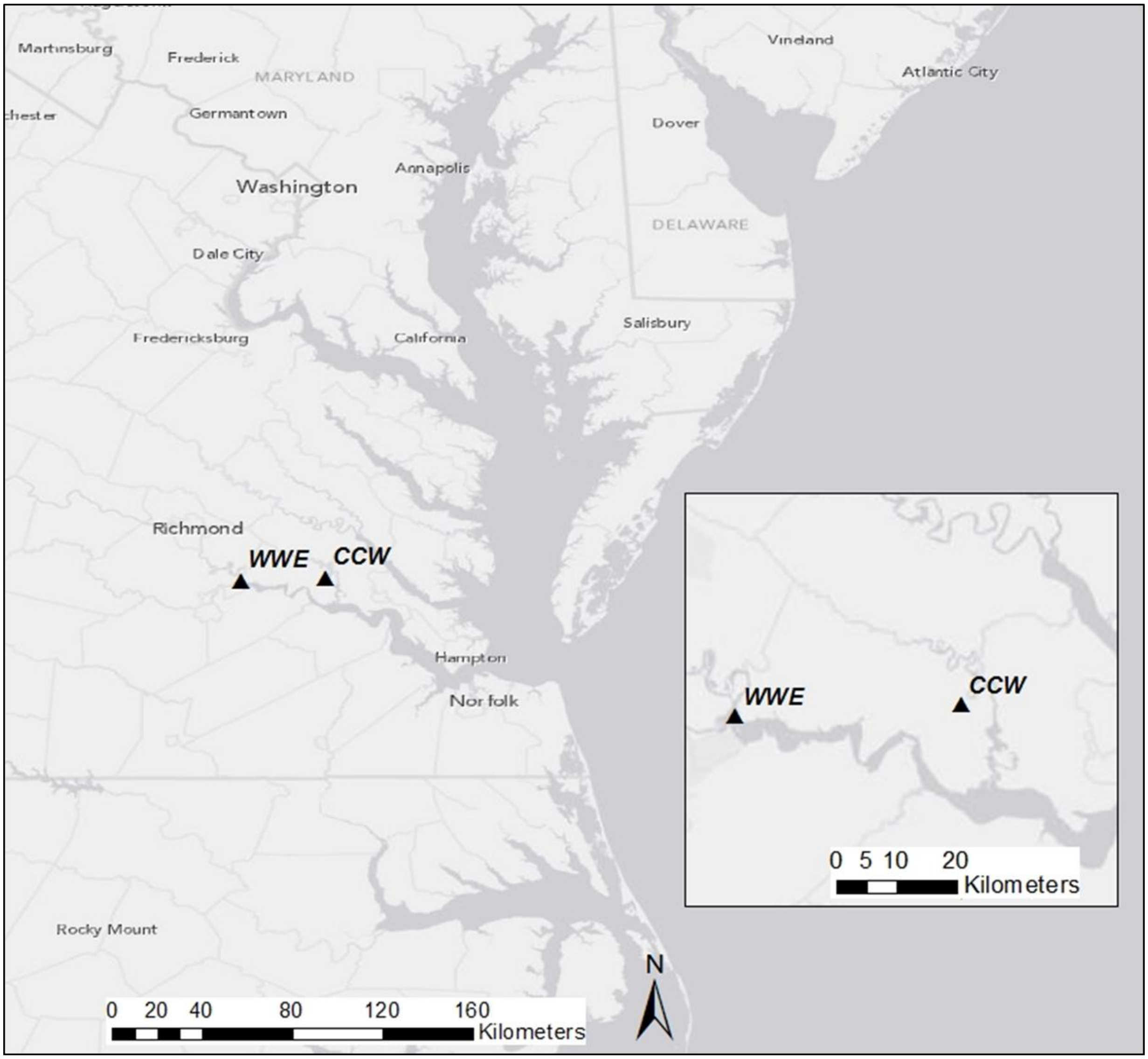

Figure 5.1. Location of the Weanack Wetland Experiment (WWE) and Charles City Wetland (CCW) in the Virginia Coastal Plain.

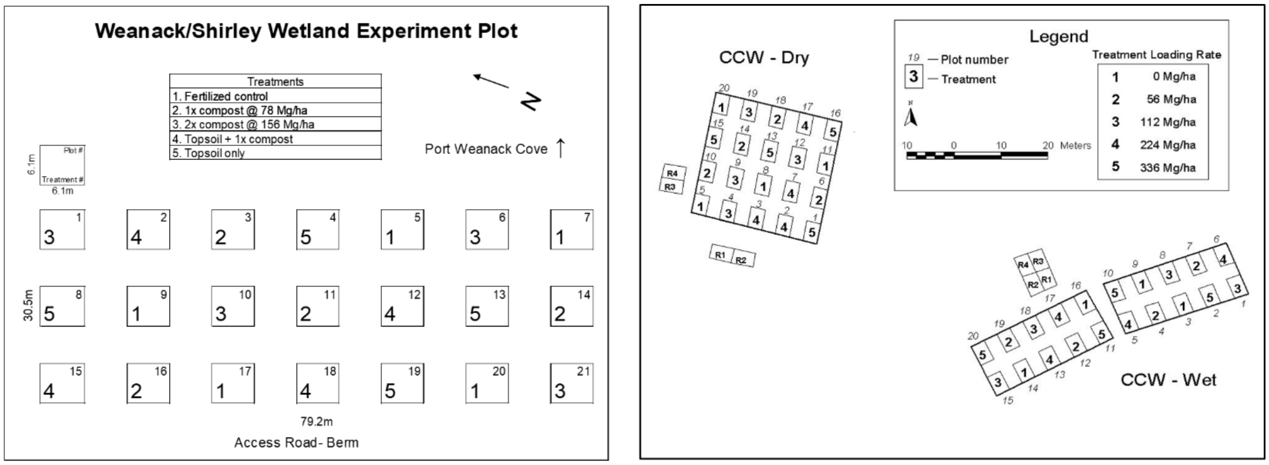

Figure 5.2. Plot layout and treatments of the wetland experiments.

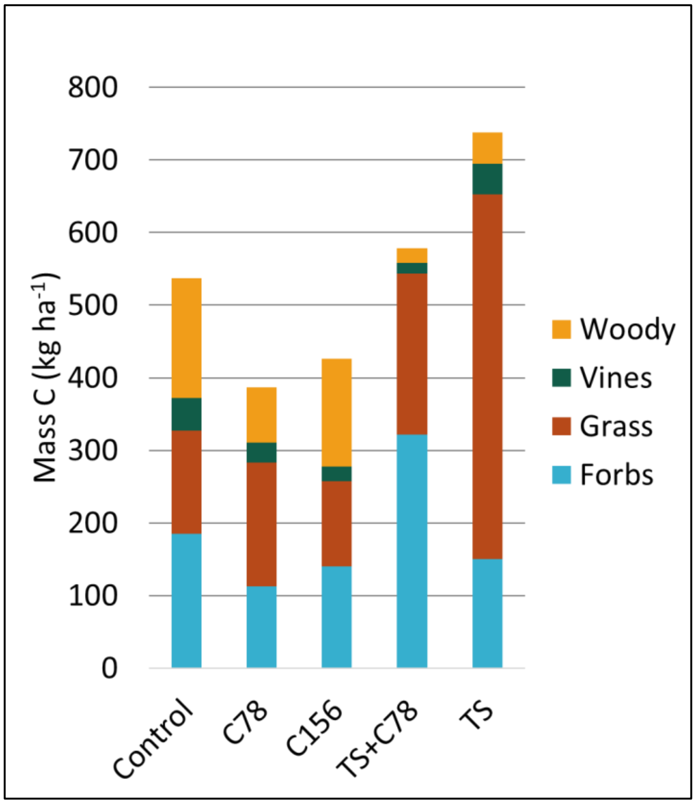

Figure 5.3. Distribution of herbaceous biomass among vegetation groups at WWE. The “woody” group includes shrubs and saplings with height < 50cm. Treatment symbols: C78 = compost at 78 Mg ha^{-1}; C156= compost at 156 Mg ha^{-1}; TS+C78 = topsoil plus 78 Mg ha^{-1} compost; TS = topsoil only.

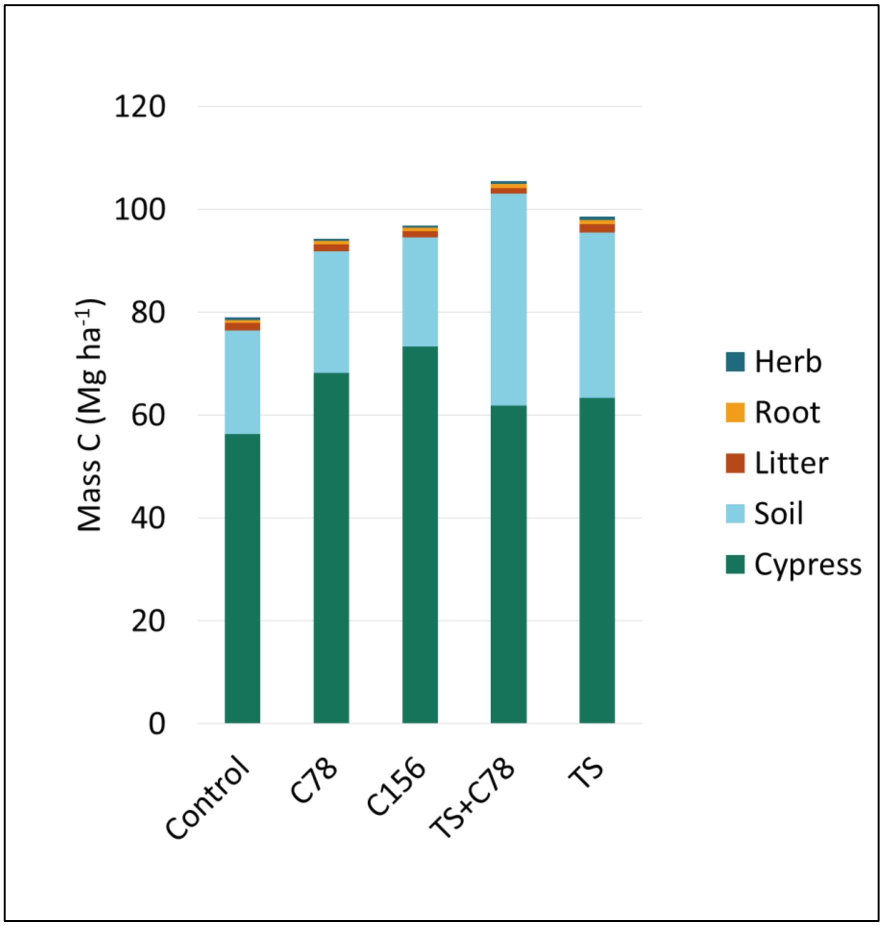

Figure 5.4. Total mass carbon at WWE, including herbaceous ("herb") biomass, root biomass, litter, soil to 30 cm, and aboveground bald cypress biomass. Treatment symbols: C78 = compost at 78 Mg ha^{-1}; C156 = compost at 156 Mg ha^{-1}; TS+C78 = topsoil plus 78 Mg ha^{-1} compost; TS = topsoil only.

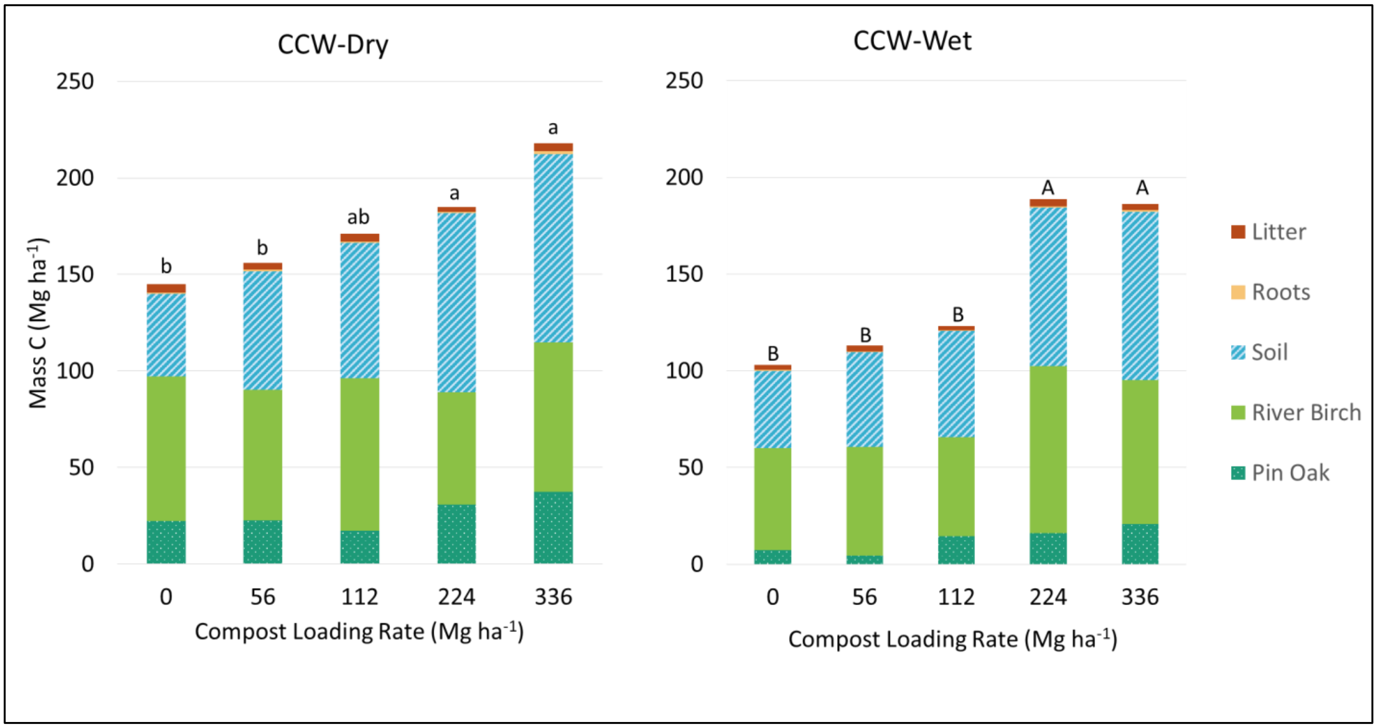

Figure 5.5. Total mass carbon at CCW, including root biomass, litter, soil to 30cm, and aboveground bald cypress biomass. Herbaceous biomass was not sampled.

6. Summary and Conclusions

Created wetlands in the past have frequently not provided essential functions such as carbon (C) sequestration, sediment trapping, floodwater retention, and groundwater recharge due to issues such as low organic carbon (OC), high soil bulk density (BD), failure to replace topsoil after excavation, incorrect hydrology (aerobic), or failure of targeted wetland vegetation establishment (i.e. facultative or upland species growing instead). Organic matter (OM) amendments help created wetlands establish vegetation and provide wetland functions during the early years after creation, but long-term OM effects have seldom been reported.

Organic matter (OM) amendments at the Weanack Wetland Experiment (WWE) had few long-term effects on soil properties. Over the 12 years since construction and treatment application at WWE, soil properties have uniformly progressed towards natural wetland soil properties, including low value and low chroma A horizons, strong gleying in the subsoil, hydric soil field indicator (HSFI) development, low BD, high OC and total nitrogen TN. The changes in these soil properties over time were not greatly influenced by compost amendments up to 156 Mg ha^{-1} (wet) The addition of fine textured topsoil over the original sandy soils led to faster soil structure development, more stable HSFI's, higher BD, and higher soil mass C over time. Sandy and loamy HSFI's formed in most plots by 2007, but there were fewer lasting sandy HSFI's by 2015. The sandy soils had fewer redox features, so many did not meet indicators S5 or S6 after 12 years. The F3 indicator was in all topsoil plots by 2015.

The mean soil mass C to 30 cm at WWE in sandy soils was 21.59 Mg C ha^{-1}, and in topsoil amended plots the mean mass C was 36.78 Mg C ha^{-1}. Biomass C at WWE was slightly affected by compost loading rate, but only in the root and grass sampling strata, which comprised a very small portion of the total mass C of the site. Most of the mass C at the site is stored in soils and cypress biomass. Herbaceous biomass in the grass fraction was higher in plots with topsoil added, possibly because of an upland seed bank present in the topsoil or the loamy texture difference. Cypress biomass (mean 64.18 Mg C ha^{-1}) did not vary by treatment and accounted for a large portion of total mass C at the site (mean 94.07 Mg C ha^{-1}), which also was not influenced by treatment.

Microtopographic pits at WWE trapped and accumulated debris and therefore had higher OC and lower BD, even though they only comprised a small fraction of the WWE wetland. The addition of microtopography in created wetlands is a valuable strategy for increasing variety of plant and animal habitats by increasing the variety of soil conditions. We recommend adding microtopography for created wetlands regardless of surface texture.

Careful construction using minimal compaction/vehicle traffic at the WWE has led to favorable site conditions (mainly low BD and shallow hydrology) that decreased the need for OM amendments to achieve long-term mitigation goals. These results may not be applicable to created wetlands with high BD or particularly for drier and non-tidal systems. It is possible that treatment effects on soil and vegetation properties over time would have been noted if compost rates greater than 156 wet Mg ha^{-1} were used. For long-term effects, we recommend adding OM to sandy created wetlands if the initial BD or hydrology is limiting.

Fourteen years after treatment applications at CCW there was a decrease in BD, an increase in OC, TN, and soil mass C with compost loading rate up to 224 Mg ha^{-1}. All plots at CCW met at least one HSFI in 2003 and 2016, but soils increased in chroma over time, so the indicator F2 was not found in 2016. There was no difference between 224 and 336 Mg ha^{-1} compost rates in these soil properties. Compost additions affected soils to about 25 cm, but did not affect the dense, clayey Btg subsoil. These results suggest that high compost loadings rates are effective in soil horizons that are loosened with mechanical disking/ripping, and that careful construction to avoid compaction is necessary. High rates of compost are difficult to incorporate into soil but provide treatment effects that last at least 14 years.

Compost additions of 224 Mg ha^{-1} increased pin oak diameter and height at CCW-Dry, but not at CCW-Wet. Compost additions had no long-term effects on river birch growth. Root biomass increased with compost, but litter C did not. Overall total mass C varied by treatment mainly due to the high soil mass C in the 224 and 336 Mg ha^{-1} treatments. Mean soil mass C to 30 cm was 92.75 Mg C ha^{-1} at CCW-Dry and 81.88 Mg C ha^{-1} at CCW-Wet. There was no difference in soil mass C or total mass C between 224 and 336 Mg ha^{-1} loading rates after 14 years, so we do not recommend rates above 224 Mg ha^{-1}.

We recommend that compost should be added to constructed wetlands similar to CCW (fine-textured, high BD, no topsoil replacement). We recommend adding 112-224 Mg ha^{-1} compost to these wetland soils for long-term effects on wetland soil BD and mass C. Rates near 112 Mg ha^{-1} stimulate early vegetation growth in the system and help replace wetland functions, whereas higher rates near 224 Mg ha^{-1} have lasting positive effects on soil properties.

Appendices

Appendix A. Official Series Descriptions

WWE:

Lakeland Series

The Lakeland series consists of very deep, excessively drained, rapid to very rapidly permeable soils on uplands. They formed in thick beds of eolian or marine and/or fluvio-marine sands in the Southern Coastal Plain MLRA (133A), the Carolina and Georgia Sandhills (MLRA 137), the Eastern Gulf Coast Flatwoods (MLRA 152A) and the Atlantic Coast Flatwoods (MLRA 153A). Near the type location, the mean annual temperature is about 67 degrees F., and the mean annual precipitation is about 52 inches. Slopes are dominantly from 0 to 12 percent but can range to 85 percent in dissected areas.

TAXONOMIC CLASS: Thermic, coated Typic Quartzipsamments

TYPICAL PEDON: Lakeland sand, in a forested area (Colors are for moist soil).

A--0 to 3 inches; very dark grayish brown (10YR 3/2) crushed and rubbed sand; single grain; loose; common uncoated sand grains; common fine and medium roots; strongly acid, clear wavy boundary. (2 to 9 inches thick)

C1--3 to 10 inches; yellowish brown (10YR 5/4) sand; common medium faint yellowish brown (10YR 5/6) mottles; single grain; loose; common fine and medium roots; few uncoated sand grains; strongly acid; gradual wavy boundary.

C2--10 to 43 inches; yellowish brown (10YR 5/8) sand; single grain; loose; few fine roots; few uncoated sand grains; strongly acid; gradual wavy boundary.

C3--43 to 64 inches; yellowish brown (10YR 5/8) sand; few medium faint very pale brown (10YR 7/3) mottles and streaks; single grain; loose; many uncoated sand grains; strongly acid; gradual wavy boundary.

C4--64 to 80 inches; very pale brown (10YR 7/4) sand; single grain; loose; many uncoated sand grains; few medium distinct yellowish red (5YR 5/8) masses of iron accumulation; strongly acid. (Combined thickness of the C horizons ranges from 71 to more than 98 inches)

TYPE LOCATION: Calhoun County, Florida; approximately 6.0 miles west of Chason on Florida State Highway 274; NE1/4, NE1/4, Sec. 3l, T. 2 N., R. l0 W.

RANGE IN CHARACTERISTICS: Thickness of the sand exceeds 80 inches. Silt plus clay in the 10 to 40-inch control section ranges from 5 to 10 percent. Reaction ranges from very strongly acid to moderately acid throughout except where the surface has been limed.

The A or Ap horizon has hue of 10YR or 2.5Y, value of 3 to 5, and chroma of l to 4. Uncoated sand grains with hue of 10YR or 2.5Y, value of 7 or 8, and chroma of 1 or 2 ranges from none to many. Texture is sand or fine sand.

Some pedons have an A/C horizon that is a mixture in shades of gray, yellow, and brown. Texture is sand or fine sand.

The C horizon has hue of 5YR to 2.5Y, value of 4 to 8, and chroma of 2 to 8. Horizons with chroma of 2 are not indicative of wetness. Small pockets of sand grains in shades of gray not related to wetness or masses of iron accumulation in shades of yellow or brown may occur in some pedons below depths of 40 inches.

Osier Series

The Osier series consists of very deep, poorly drained, rapidly permeable soils on flood plains or low stream terraces. They formed in sandy alluvium. Near the type location, the mean annual temperature is about 67 degrees F, and the mean annual precipitation is about 46 inches. Slopes range from 0 to 2 percent.

TAXONOMIC CLASS: Siliceous, thermic Typic Psammaquents

TYPICAL PEDON: Osier loamy fine sand - forested. (Colors are for moist soil stated.)

A1--0 to 3 inches; very dark grayish brown (10YR 3/2) loamy fine sand; moderate fine granular structure; very friable; many fine and coarse roots; very strongly acid; abrupt wavy boundary.

A2--3 to 8 inches; mixed dark gray (10YR 4/1) and grayish brown (2.5Y 5/2) loamy sand; weak medium granular structure; very friable; common fine and coarse roots; thin strata of sand; very strongly acid; clear wavy boundary. (Combined thickness of the A horizons ranges from 2 to 20 inches.)

Cg1--8 to 16 inches; dark gray (10YR 4/1) loamy sand; weak fine granular structure; very friable; common fine roots; thin strata of gray (10YR 6/1) sand; very strongly acid; gradual wavy boundary.

Cg2--16 to 36 inches; gray (10YR 6/1) sand; single grained; loose; few fine roots; few fine distinct yellowish brown (10YR 5/6) masses of iron accumulation; very strongly acid; gradual wavy boundary.

Cg3--36 to 48 inches; light brownish gray (2.5Y 6/2) sand; single grained; loose; few fine roots; common coarse distinct brownish yellow (10YR 6/6) masses of iron accumulation; very strongly acid; gradual wavy boundary.

Cg4--48 to 60 inches; light gray (2.5Y 7/2) coarse sand; single grained; loose; few fine distinct yellowish brown (10YR 5/6) masses of iron accumulation; common medium faint light brownish gray (2.5Y 6/2) areas of iron depletions; very strongly acid; gradual wavy boundary.

Cg5--60 to 75 inches; dark gray (10YR 4/1) coarse sand; single grained; loose; many coarse faint light brownish gray (10YR 6/2) areas of iron depletions; very strongly acid.

TYPE LOCATION: Irwin County, Georgia. Approximately 4 miles south of Ocilla, Georgia, along U.S. Highway 129, about 2.3 miles southwest along county road, and about 250 feet east of road in wooded bottom area.

RANGE IN CHARACTERISTICS: Thickness of the sand is 80 inches, or more. Reaction ranges from extremely acid to moderately acid throughout the profile. The silt plus clay content of the 10 to 40-inch zone is 5 to 15 percent.

The A horizon has hue of 10YR or 2.5Y, value of 2 to 5, and chroma of 1 or 2. Where the value is 2 or 3, it is less than 10 inches thick. Texture is fine sandy loam, loamy fine sand, loamy sand, fine sand or sand.

The C horizon has hue of 7.5YR to 5GY, value of 3 to 8, and chroma of 1 or 2; or it is neutral with value of 5 to 7. Redoximorphic features in shades of brown, yellow, and gray range from none to common. Texture is loamy fine sand, loamy sand, fine sand, sand; and in the lower Cg horizons, can include coarse sand. Most pedons have thin strata of material ranging from sand to sandy loam.

In some pedons, the C horizon is underlain or interrupted by an Ab horizon. It has hue of 10YR to 5Y, value of 2 or 3, and chroma of 1 or 2. Texture is fine sand, loamy fine sand, or loamy sand.

Pamunkey Series

Soils of the Pamunkey series are very deep and well drained. They formed in Piedmont and Coastal Plain sediments. They are on nearly level to sloping stream terraces. Slopes range from 0 to 15 percent. Mean annual precipitation is about 48 inches, and mean annual temperature is about 59 degrees F.

TAXONOMIC CLASS: Fine-loamy, mixed, semiactive, thermic Ultic Hapludalfs

TYPICAL PEDON: Pamunkey fine sandy loam - cultivated. (Colors are for moist soil.)

Ap--0 to 9 inches dark brown (7.5YR 4/4) fine sandy loam; moderate fine granular structure; very friable, slightly sticky, nonplastic; many fine and medium roots; 3 percent rounded quartz gravel; few fine flakes of mica; neutral; abrupt smooth boundary. (6 to 12 inches thick)

Bt1--9 to 11 inches; yellowish red (5YR 4/6) sandy clay loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; many fine roots; few faint clay films on faces of peds; 1 percent rounded quartz gravel; few fine flakes of mica; slightly acid; clear smooth boundary.

Bt2--11 to 26 inches; yellowish red (5YR 4/6) clay loam; moderate medium subangular blocky structure; friable, slightly sticky, slightly plastic; common fine roots; common distinct clay films on faces of peds; common black stains on vertical faces of peds; 5 percent rounded quartz gravel; few fine flakes of mica; slightly acid; gradual smooth boundary.

Bt3--26 to 43 inches; yellowish red (5YR 4/8) sandy clay loam; weak coarse subangular blocky structure; friable, slightly sticky, slightly plastic; few fine roots; common faint clay films on faces of peds; common black coatings on faces of peds; 5 percent rounded quartz gravel; few fine flakes of mica; slightly acid; gradual smooth boundary. (Combined thickness of the Bt horizon ranges from 35 to 60 inches.)

BC--43 to 46 inches; yellowish red (5YR 4/8) sandy loam; weak fine subangular blocky structure; friable, slightly sticky, nonplastic; few faint clay films on faces of peds; common black stains; 10 percent rounded quartz gravel; common fine flakes of mica; moderately acid; abrupt wavy boundary. (30 to 12 inches thick) 30 to 60 inches)

2C--46 to 80 inches; stratified layers of yellowish brown (1OYR 5/6), strong brown (7.5YR 5/6), and reddish brown (5YR 4/4) sand and rounded greenstone and granite gravel; single grain; loose; few cobbles; common fine flakes of mica; medium acid.

TYPE LOCATION: Hanover County, Virginia; near Camp Town Race Track, 1 mile east of Interstate 95 and 250 feet south of the South anna River.

RANGE IN CHARACTERISTICS: Solum thickness and depth to unconforming strata range from 40 to 60 inches or more. Depth to hard bedrock is more than 80 inches. Gravel lines are at varying depths in some pedons, normally below 40 inches. Rock fragments, usually rounded gravel and a few cobbles, make up 0 to 15 percent of the solum and 0 to 35 percent of the substratum. The soil ranges from very strongly acid through slightly acid in the solum and from moderately acid through neutral in the substratum, unless limed.

The A or Ap horizon has hue of 5YR through 1OYR, value of 3 through 6, and chroma of 2 through 4. The A horizon is loamy sand, fine sandy loam, sandy loam, loam, or silt loam. It is silty clay loam, sandy clay loam, or clay loam in eroded areas.

The E horizon, where present, has hue of 5YR through 10YR, value of 5 or 6, and chroma of 2 through 4. The E horizon is loamy sand, fine sandy loam, sandy loam, loam, or silt loam.

The BE or BA, horizon, where present, has hue of 2.5YR through 1OYR, value of 4 through 6, and chroma of 3 through 8. It is sandy loam, fine sandy loam, or loam.

The Bt horizon has hue of 2.5YR through 1OYR, value of 4 through 6, and chroma of 3 through 8. It is fine sandy loam, loam, silt loam, sandy clay loam, clay loam, or silty clay loam. Flakes of mica range from few to many. Dark stains or concretions are in most pedons.

The BC or CB horizon, where present, has colors similar to those of the Bt horizon. It is loamy sandy, sandy loam, fine sandy loam, or loam.

The C or 2C horizon has colors similar to those of the Bt horizon. It commonly consists of sandy and loamy strata containing gravels, cobbles, and a few boulders. Some pedons have strata of finer texture.

Chickahominy Series

Soils of the Chickahominy series are very deep and poorly drained with very slow permeability. They formed in clayey fluvial sediments on Coastal Plain river terraces. Slopes range from 0 to 2 percent. Mean annual precipitation is about 45 inches and mean annual temperature is about 59 degrees F.

TAXONOMIC CLASS: Fine, mixed, semiactive, thermic Typic Endoaquults

TYPICAL PEDON: Chickahominy silt loam - on a 1 percent slope in woodland. (Colors are for moist soil unless otherwise stated.)

A--0 to 2 inches; dark grayish brown (2.5Y 4/2) silt loam; moderate medium and fine granular structure; friable, sticky, plastic; many fine medium and coarse roots; few very fine tubular pores; extremely acid; abrupt smooth boundary. (1 to 4 inches thick)

Eg--2 to 7 inches; dark grayish brown (2.5Y 4/2) silt loam; common fine faint light olive brown (2.5Y 5/4) mottles and common fine distinct very dark grayish brown (1OYR 3/2) mottles; moderate medium granular and weak fine subangular blocky structure; friable, sticky, plastic; many fine medium and coarse roots; common very fine tubular pores; few fine flakes of mica; extremely acid; clear smooth boundary. (0 to 10 inches thick)

Btg1--7 to 13 inches; gray (N 6/0) silty clay loam; common medium prominent yellowish brown (1OYR 5/8) mottles; strong medium and fine subangular blocky structure; very firm, sticky, plastic; common fine medium and coarse roots; few very fine tubular pores; few faint clay films on faces of peds; few fine flakes of mica; extremely acid; gradual smooth boundary.

Btg2--13 to 33 inches; gray (N 6/0) silty clay; common fine and medium prominent yellowish brown (1OYR 5/8) mottles; weak medium prismatic structure parting to strong fine and medium angular blocky; very firm, sticky, plastic; common fine and medium roots along primary structural faces; few very fine tubular pores; common distinct clay films on faces of peds; few fine flakes of mica; very strongly acid; gradual smooth boundary.

Btg3--33 to 47 inches; gray (5Y 6/1) silty clay; common medium Prominent yellowish brown (1OYR 5/8) mottles; moderate coarse prismatic structure parting to strong medium and fine angular blocky; very firm, sticky, plastic; common fine and few medium roots along primary structural faces; common prominent clay films on faces of peds; few fine roots of mica; extremely acid; gradual smooth boundary.

Btg4--47 to 61 inches; gray (5Y 5/1) silty clay; common medium prominent yellowish brown (1OYR 5/8) mottles; strong medium and fine subangular and angular blocky structure; firm, sticky, plastic; few fine and medium roots; few prominent clay films on faces of peds; few fine flakes of mica; very strongly acid; gradual smooth boundary.

Btg5--61 to 85 inches; gray (5Y 6/1) clay loam; common medium prominent yellowish brown (1OYR 5/8) mottles; strong medium and fine subangular and angular blocky structure; firm, sticky, plastic; few fine roots; few very fine tubular pores; few prominent clay films on faces of peds; few fine flakes of mica; very strongly acid. (Combined thickness of toe Bt horizon is 50 to more than 80 inches)

TYPE LOCATION: James City County, Virginia; approximately 300 feet west of intersection of VA-5 and VA-613, 100 feet south of VA-5.

RANGE IN CHARACTERISTICS: The solum thickness ranges from 60 to 80 inches or more. Quartz gravel make up 0 to 2 percent of the solum. The particle-size control section has more than 30 percent silt. Aluminum saturation on the exchange complex is commonly more than 50 percent and ranges from 10 to 25 meq/100 grams of soil. Fine flakes of mica range from few to common in most pedons. The soil is extremely acid through strongly acid unless limed.

The A horizon has hue of 10YR through 5Y, value of 3 through 6, and chroma of 1 or 2. Where value is 3 it is less than 6 inches thick. It is very fine sandy loam, loam, or silt loam.

The Eg horizon has hue of 10YR through 5Y, value of 3 through 6, and chroma of 1 or 2. Some pedons have high and low chroma mottles. The E horizon is very fine sandy loam, loam, or silt loam.

The BAg horizon, where present, has hue of 10YR through 5Y or it is neutral, value of 4 through 6, and chroma 0 through 2. High chroma mottles are in some pedons. It is loam, silt loam, clay loam, or silty clay loam.

The EBg or BEg horizon, where present, has hue of 1OYR through 5Y or they are neutral, value of 4 through 6, and chroma of 0 through 2. High chroma mottles are in some pedons. Texture is loam, silt loam, clay loam, or silty clay loam.

The Btg horizon has hue of 1OYR through 5Y or it is neutral, value of 4 through 7, and chroma of 0 through 2. High chroma mottles are in most pedons. It is clay loam, silty clay loam, silty clay, or clay.

The Cg horizon where present, has hue of 10YR through 5Y, or it is mottled. It commonly is stratified and ranges from sand through clay. rock fragments range from 0 to 15 percent.

Newflat Series

Soils of the Newflat series are very deep and somewhat poorly drained with very slow permeability. They formed in clayey fluvial sediments on Coastal Plain river terraces. Slopes range from 0 to 2 percent. Mean annual precipitation is about 42 inches and mean annual temperature is about 59 degrees F.

TAXONOMIC CLASS: Fine, mixed, subactive, thermic Aeric Endoaquults

TYPICAL PEDON: Newflat silt loam - on a 1 percent slope in woodland. (Colors are for moist soil unless otherwise stated.)

Oi--1 to 0 inch; leaf litter and partially decomposed organic materials.

A--0 to 2 inches; very dark gray (10YR 3/1) silt loam; moderate fine granular structure; very friable; many fine and common medium roots; extremely acid; clear smooth boundary. (0 to 4 inches thick)

E--2 to 5 inches; light brownish gray (10YR 6/2) silt loam; few fine faint light yellowish brown (1OYR 6/4) and few fine distinct yellowish brown (10YR 5/6) masses of iron accumulation; moderate fine granular structure; very friable, slightly sticky, common fine roots; extremely acid; gradual smooth boundary. (0 to 4 inches thick)

Bt--5 to 10 inches; light yellowish brown (10YR 6/4) clay loam; few fine distinct light gray (1OYR 7/1) iron depletions and many coarse faint brownish yellow (10YR 6/6) masses of iron accumulation; weak fine subangular blocky structure; friable, slightly sticky, slightly plastic; few fine roots; few distinct clay films on faces of peds; extremely acid; gradual smooth boundary. (0 to 6 inches thick)

Btg1--10 to 20 inches; light brownish gray (10YR 6/2) clay loam; common medium distinct yellowish brown (10YR 5/6) and strong brown (7.5YR 5/6) masses of iron accumulation; moderate medium prismatic structure parting to moderate fine and medium angular blocky; firm, very sticky, plastic, few fine roots; common distinct clay films on faces of peds; extremely acid; gradual smooth boundary.

Btg2--20 to 35 inches; gray (10YR 6/1) clay loam; common medium distinct yellowish brown (1OYR 5/6) and strong brown (7.5YR 5/6) masses of iron accumulation; moderate medium prismatic structure parting to moderate fine and medium angular blocky; firm, very sticky, very plastic; few fine roots; common distinct clay films on faces of peds; extremely acid; gradual smooth boundary.

Btg3--35 to 75 inches; light gray (10YR 6/1) silty clay; common medium distinct strong brown (7.5YR 5/6) masses of iron accumulation; moderate medium subangular blocky structure; firm, very plastic; thin patchy clay films on faces of peds; extremely acid. (Combined thickness of the Btg horizon is 55 to more than 90 inches thick)

TYPE LOCATION: Prince George County, Virginia; approximately 550 yards southwest of intersection of VA-10 and VA-616, 25 yards south of VA-616.

RANGE IN CHARACTERISTICS: The solum thickness ranges from 60 to 90 inches or more. The soil is extremely acid through strongly acid unless limed. Quartz gravel make up 0 to 2 percent of the solum. The particle-size control section has more than 30 percent silt. Aluminum saturation on the exchange complex is commonly greater than 50 percent and ranges from 10 to 20 meq/100 grams of soil. Fine flakes of mica range from few to common in some pedons.

The A horizon has hue of 1OYR or 2.5Y or it is neutral, value of 3 through 5, and chroma of 0 through 2. Horizons with value of 3 are 6 inches or less thick. The A horizon is very fine sandy loam, loam, or silt loam.

The Ap horizon has hue of 1OYR or 2.5Y or it is neutral, value of 3 through 5, and chroma of 0 through 2. Horizons with value of 3 are 6 inches or less thick. The Ap horizon is very fine sandy loam, loam, or silt loam.

The E horizon has hue of 10YR or 2.5Y, value of 5 through 7, and chroma of 2 through 4. The E horizon is very fine sandy loam, loam, or silt loam.

The BE horizon, where present, has hue of 1OYR through 5Y, value of 5 or 6, and chroma of 3 through 6. In some pedons, it is mottled with gray. It is loam, silt loam, clay loam, or silty clay loam.

The Bt horizon, where present, has hue of 10YR through 5Y, value of 5 or 6, and chroma of 3 through 6. It has common to many high and low chroma redox features. It is clay loam, silty clay loam, silty clay, or clay.

The Btg horizon has hue of 1OYR through 5Y, value of 4 through 7, and chroma of 0 through 2. It has common to many high chroma redox features. The Btg horizon is clay loam, silty clay loam, silty clay or clay.

The BC horizon where present, has hue of 10YR through 5Y or it is neutral, value of 4 through 7, and chroma of 0 through 2. It is loam, silt loam, sandy clay loam, clay loam, or clay.

The C horizon has hue of 1OYR through 5Y or it is neutral, value of 4 through 7, and chroma of 0 through 2. It ranges from fine sandy loam through clay.

Appendix B. Hydric Soil Indicators

A11. —Depleted Below Dark Surface.

For use in all LRRs, except for W, X, and Y; for testing in LRRs W, X, and Y. A layer with a depleted or gleyed matrix that has 60 percent or more chroma of 2 or less, starting at a depth ≤30 cm (12 inches) from the soil surface, and having a minimum thickness of either: a. 15 cm (6 inches), or b. 5 cm (2 inches) if the 5 cm consists of fragmental soil material. Organic, loamy, or clayey layer(s) above the depleted or gleyed matrix must have value of 3 or less and chroma of 2 or less starting at a depth ≤15 cm (6 inches) from the soil surface and extend to the depleted or gleyed matrix. Any sandy material above the depleted or gleyed matrix must have value of 3 or less and chroma of 1 or less starting at a depth ≤15 cm (6 inches) from the soil surface and extend to the depleted or gleyed matrix. Viewed through a 10x or 15x hand lens, at least 70 percent of the visible sand particles must be masked with organic material. Observed without a hand lens, the sand particle.

S5. —Sandy Redox.

For use in all LRRs, except for Q, V, W, X, and Y. A layer starting at a depth ≤15 cm (6 inches) from the soil surface that is at least 10 cm (4 inches) thick and has a matrix with 60 percent or more chroma of 2 or less and 2 percent or more distinct or prominent redox concentrations occurring as soft masses and/or pore linings.

S6. —Stripped Matrix.

For use in all LRRs, except for V, W, X, and Y. A layer starting at a depth ≤15 cm (6 inches) from the soil surface in which iron manganese oxides and/or organic matter have been stripped from the matrix and the primary base color of the soil material has been exposed. The stripped areas and translocated oxides and/or organic matter form a faintly contrasting pattern of two or more colors with diffuse boundaries. The stripped zones are 10 percent or more of the volume and are rounded.

F2. —Loamy Gleyed Matrix.

For use in all LRRs, except for W, X, and Y. A gleyed matrix that occupies 60 percent or more of a layer starting at a depth ≤30 cm (12 inches) from the soil surface (fig. 28).

F3. —Depleted Matrix.

For use in all LRRs, except W, X, and Y; for testing in LRRs W, X, and Y. A layer that has a depleted matrix with 60 percent or more chroma of 2 or less and that has a minimum thickness of either:

a. 5 cm (2 inches) if the 5 cm starts at a depth ≤10 cm (4 inches) from the soil surface, or

b. 15 cm (6 inches), starting at a depth ≤25 cm (10 inches) from the soil surface.

Appendix C. 2015 WWE Soil Descriptions.

	Horizon			Texture		Matrix	Structure				Redox Features			
Plot	Name	Lower depth (cm)	Boundary	USDA Class	Clay %	Hue value/chroma	Grade	Size	Shape	Cons.	Depletions	Concentrations	Roots (quantity and size)	Pores
							Treatment 1: Fertilized Control							
5	A	9	A	Loamy Sand	2	10YR 2/2	wk	f	sbk	vfr	0%	2% 7.5YR 5/6, sm	m vf, m f, f m, f co	-
	C	22	A	Sand	1	10YR 6/3	sls	-	sg	lo	2% 10YR 6/1, sm	13% 7.5YR 6/6, sm	c vf, c f, f m, f co	-
												9% 7.5YR 7/6, sm		
	Cg	30		Sand	1	2.5Y 5/2	sls	-	sg	lo	1% 2.5Y 7/2, sm	1% 7.5YR 5/8, sm	f vf-c	-
												5% 2.5Y 4/2 (OM)		
7	A	8	A	Loamy Sand	2	10YR 2/2	Wk	f	sbk	vfr	0%	0%	m vf-f, f m-co	-
	C	26	A	Sand	1	10YR 6/3	Sls	-	sg	lo	1% 2.5Y 6/1, sm	1% 7.5YR 5/8, sm	c vf-f, f m-co	-
												3% 7.5YR 6/8, sm		
	Cg	30	-	Sand	1	2.5Y 5/2	Sls	-	sg	lo	0%	1% 5YR 4/6, sm 2% 5YR 6/8	f f	-
												2% 5YR 6/6		
9	A	4	A	Loamy sand	2	10YR 2/1	Wk	f	sbk	vfr	20% 5Y 5/1, sm	5% 5YR 5/8, sm	m vf, m f, f m	-
	Cg	30		Sand	1	2.5Y 6/2	Sls	-	sg	lo		1% 5YR 4/6, sm	f vf-c	-

17	A	3	A	Loamy sand	2	10YR 2/1	Wk	f	sbk	vfr	0%	0%	m vf, m f, f m	-
	C	10	A	Sand	1	10YR 5/3	Sls	-	sg	lo	2% 10YR 5/2, sm	2% 5YR 5/8, sm	f vf-m	-
	Cg1	26	A	Sand	1	2.5Y 5/2	Sls	-	sg	lo	2% 2.5Y 6/2, sm	3% 5YR 5/8, sm	f vf	-
	Cg2	30	-	Sand	1	2.5Y 5/1	Sls	-	sg	lo	-	1% 5YR 4/6, sm	f vf	-
20	A	2	A	Loamy sand		10YR 3/1	sls	-	ma	lo	0%	0%	m vf-m	-
	C	31+	--	Sand		10YR 4/3	sls	-	sg	lo	25% 10YR 6/2, m+c sm	5% 5YR 4/6, rc	c vf-m	-
												25% 10YR 5/6, sm		

Treatment 2: 78 Mg ha^{-1} Compost

3	A	5	A	Loamy sand	2	10YR 2/3	wk	f	sbk	vfr	0%	0%	m vf-f, m m	-
	C	15	A	Sand	1	10YR 5/3	sls	-	sg	lo	2% 2.5Y 6/1, sm	3% 5YR 5/6, sm	c vf-f	-
						10YR 4/3								
	C	27	A	Sand	1	10YR 5/3	sls	-	sg	lo		20% 7.5YR 5/6, sm	f vf	-
												10% 5YR 5/8, sm		
												1% 2.5YR 4/8, sm		
	Cg	30---	-	Sand	1	2.5Y 6/2	sls	-	sg	lo	-	1% 5YR 5/8, sm	-	-
11	A	6	A	Loamy sand	2	10YR 3/2	wk	f	sbk	vfr	0%	0%	m vf-f, f m	-
	C	22	A	Sand	1	10YR 5/3	sls	-	sg	lo	2%2.5Y6/1, sm	4% 7.5YR 6/8, sm	c vf-f, f m	-

	Cg	30	-	Sand	1	2.5Y 4/1	sls	-	sg	lo	-	1% 7.5YR 5/8, sm	f vf	-
												1% 7.5YR 6/8, sm		
												2%10YR 2/1 (OM)		
												3% 10YR 3/1 (OM)		
14	A	5	A	Loamy sand	2	10YR 2/2	wk	f	sbk	vfr	0%	0%	m vf-f, f m-co	-
	C	21	A	Sand	1	10YR 6/3	sls	-	sg	lo	5% 10YR 6/2, sm	1% 5YR 4/6, sm	c vf-f, f m	-
												8% 7.5YR 5/8, sm		
	Cg	30	-	Sand	1	2.5Y 5/2	sls	-	sg	lo	1% 2.5Y 7/1	7% 7.5YR 7/8, sm	f vf	-
												1% 7.5YR 4/6, sm		
												1% 7.5YR 6/8, sm		
16	Ap	6	A	Sand		10YR 2/2	mo	m	sbk	vfr	0%	0%		vf vf
	Cg1	28	C	Sand		2.5Y 5/1	sls		sg	lo		2% 7.5Y 4/6	f vf, f f, m m	-
												10% 7.5YR 5/6		
												18% 10YR 4/2		
	Cg2	30+	-	Sand		2..5Y 4/1	sls		sg	lo	0%	5% 10YR 4/2		-

Treatment 3: 156 Mg ha^{-1} Compost

1	A	3	A	Loamy Sand	2	10YR 2/1	Wk	f	sbk	vfr	0%	0%	m vf-f, f m	-
	C	19	A	Sand	1	2.5Y 4/3	Sls	-	sg	lo	5% 10YR 5/2, sm	3% 5YR 4/6, sm	f vf, f f, f m	-
												10% 7.5YR 4/6		
	Cg	30+	-	Sand	1	5Y 6/1	Sls	-	sg	lo	0%	5% 5YR 4/6, sm	f m	-

												3% 7.5YR 4/6		
6	Ap	5	A	Loamy sand		10YR 2/2	Mo	f	sbk	vfr	0%	0%	m f-m	f f
	Cg1	18		Sand		2.5Y 5/2	Sls	-	ma	lo	5% N 5/0	10% 10YR 5/3	c vf-f, m m	c vf
												20% 7.5YR 5/6		
	Cg2	30+		Sand		2.5Y 5/2	sls		ma	lo		10% 7.5YR 5/6	f vf-f, c m	-
												10% 7.5YR 4/6		
												10% 10YR 5/3		
10	A	9	A	Loamy Sand	2	10 YR 3/2	wk	f	sbk	vfr	0%	0%	m vf, m f, f m, f co	-
	C	20	A	Sand	1	10YR 6/3	sls	-	sg	lo	1% 2.5Y 7/1, sm	1% 5YR 4/6, sm	f m, f f, f vf	-
												5% 5YR 6/6, sm		
	Cg1	27	A	Sand	1	10YR 6/2 30% 10YR 4/1	sls	-	sg	lo	1% 2.5Y 6/1, sm	1% 5YR 4/6, sm 1% 5YR 6/6, sm	f f	-
	Cg2	30+	-	Sand	1	80% 2.5Y 4/1 20% 2.5Y 3/1	sls	-	sg	lo	1% 2.5Y 6/1, sm	2% 7.5YR 5/6 1% 2.5YR 4/8	f f	-
21	A	6	A	Loamy sand	2	10YR 2/2	wk	f	sbk	vfr	0%	0%	m vf, m f, c c, f m	-
	Cg2	30+		Sand	1	2.5YR 5/3	sls		sg	lo	5% 2.5Y 6/2, sm	10%, 7.5YR 5/8, sm	c f, c vf, f m	-
												5% 5YR 5/8, sm		

Treatment 4: Topsoil + 78 Mg ha^{-1} Compost

2	A	5	A	Loam	16	10 YR 3/3	mo	m	G	vfr	0%	2% 7.5 YR 5/8, sm	m vf, m f, f m	-

	Bg1	14	A	Loam	22	10 YR 4/2	wk	m	sbk	fr	5% 2.5YR 5/1, sm	15% 5YR 5/8, sm		c vf
												1% Mn		
	Bg2	21	A	Clay Loam	28	2.5 Y 5/2	wk	m	sbk	fr	2% 10YR 5/1, sm	3% 7.5YR 4/6, rc		c vf
												5% 7.5YR 5/6, sm		
	2^C	30+	-	Sand	1	10 YR 5/3	sls	-	sg	lo	2% 5Y 6/1, sm	1% 2.5 YR 4/8, sm		-
											20% 2.5Y 6/2	7% 5YR 5/8		
												10% 7.5YR 6/8, sm		
12	A	5	A	Silt loam		10YR 3.5/2	wk	f-m	sbk		0%	0%	m vf-f, c m-co	-
	Bg1	12	A	Silt loam		10YR 5/2	wk	m-co	sbk		10YR 5/2, f f pl	10YR4/4, c f sm	c vf-f, f m-co	f f-m
												1% Mn		
	Bg2	19	A	Silt loam		10YR 5/2	wk	co	sbk		10YR 5/1, c f	7.5YR 4/6, m pl+sm	c vf-f, f m-co	f f-m
												7.5YR 4/6, f f		
	2^C	32+	--	Sand		10YR 5/3	sls	--	sg		25% 10YR 4/1	25% 10YR 4/4, sm	f vf-m	-
												5YR 4/6, f f rc		
15	A	2	A	Silt loam	15	10YR 3/2	mo	m	gr	fr	0%	0%	m vf, m f, f m	-
	Bw	13	A	Silt loam	15	10YR 5/3	mo	m	sbk	fr	6% 10YR 4/2, sm	1% (Mn) 10YR 2/1, sm 15% Fe 5YR 5/8-6/8,rc+pl+sm	m vf, m f, f m	c vf

	Bg	18	A	Silt loam	15	2.5Y 5/2	wk	m	sbk	fr	0%	15% Fe 5YR 4/6, pl+sm 2% Fe 5YR 5/6, rc	c vf, c f	c vf
	2^Cg	30+	-	Sand	1	2.5Y 5/1	sls		ma	lo	7% 2.5YR 4/1, sm	2% 5YR 4/6, sm 1% 5YR 5/6, sm	vf vf	-
18	A	5	A	Loam	10	10YR 3/2	wk	m	gr	vfr	0%	0%	m vf, m f, f m	-
	Bg	23	A	Silt Loam	20	5Y 5/2	wk	m	sbk	fr	0%	2% 10YR 5/6, sm 1%7.5YR 5/6, sm	c vf, c f, f m	c vf
	2^Cg	30+	-	Sand	1	50% 5Y 5/1 50% 2.5Y 6/2	sls		sg	lo	0%	1% 2.5YR 5/8, sm	c vf, c f	-

Treatment 5: Topsoil

4	A		C	Loam	16	10YR 3/2	mo	m	gr	vfr	0%	0%	m vf-f, f m	-
	Bg		A	Loam	21	10YR 5/2	mo	m	sbk	fr	5% 10YR 6/2, sm 3% 2.5Y 6/1, sm	4% 7.5YR 4/6, rc+pl+sm 4% 7.5YR 5/7, rc+pl+sm 1% 2.5YR 4/8, rc+pl+sm 1% 10YR 2/1 (Mn)	c vf	c vf
	2^Cg	30---	-	Sand	1	10YR 4/2	sls	-	sg	lo	4%10YR 6/1 sm	2% 5YR 5/8, sm 15% 5YR 5/6, sm	f vf, vf m	-
8	A	4	A	Loam	15	10YR 3/2	mo	m	gr	vfr	0%	0%	m vf-f, f m	-
	Bg	14	A	Silt loam	15	10 YR 5/2	wk	m	sbk	fr	20% 10YR 5/1, sm	5% 5YR 4/6, rc	m vf-f, f m	c vf-f

												6% 7.5YR 5/6, sm		
												1% 10YR 2/1 pores (Mn)		
	2^C	22	A	Sand	1	10YR 5/3	sls	-	sg	lo	15% 10YR 5/2, sm	2% 7.5YR 5/8, sm	c vf-f	c vf
												10% 10YR 6/8, sm		
	2^Cg	30--	-	Sand	1	10YR 4/1	sls	-	sg	lo	7% 2.5Y 4/1, sm	2% 5YR 5/8, sm	vf vf	-
												1% 2.5Y 5/6, sm		
13	Ap	4	A	Loam		10YR 3/4	mo	f	sbk	vfr	0%	2% 10YR 3/6, rc+pl	m vf-m	-
							mo	m	sbk					
	Bg	13	A	Loam		2.5Y 5/2	wk	f	sbk	fr	0%	30% 7.5YR 4/6, rc+pl+sm	m vf-m	c vf
												2% Mn		
	Cg	20	C	Loam		2.5Y 5/1	sls		ma	fr	0%	5% 7.5YR 5/6, rc+sm	m f, c vf	f vf
												5% 7.5YR 4/3		
	2^Cg	30+	-	Sand		2.5Y 5/2	sls		sg	lo	0%	20% 10YR 5/3, rc	vf vf-f	-
												5% 7.5YR 4/6		
												5 %7.5YR 5/6		
19	A	3	A	Loam		10YR 3/3	mo	m	gr	vfr	0%	0%	m vf-f, f m	-
	Bg1	13	A	Silt loam		2.5Y 5/2	mo	m	sbk	fr	1% 2.5Y 6/2, sm	5% 7.5YR 5/6, pl+sm	c vf-m	f vf
												2% 7.5YR 5/8, pl		

Bg2	20	A	Silt loam	10YR 5/2	wk	m	sbk	fr	0%	4% 7.5YR 5/6, sm	f vf-f	f vf
2^C	30---	-	Sand	5Y 5/1	sls	-	sg	lo	0%	1% 2.5YR4/8, sm	f vf	
										1% 7/5YR 5/8		

Appendix D. CCW Soil Descriptions

Table D1. Soil descriptions at CCW-Dry. Descriptions were made on October 22 and 23, 2016.

	Horizon			Rock Fragments		Texture		Matrix Color	Structure				Redox Features	
Plot	Name	Lower depth (cm)	Boundary	%	Shape	USDA Class	Clay %	Hue value/chroma	Grade	Size	Shape	Moist Cons.	Depletions	Concentrations
								Treatment 1: 0 Mg ha^{-1} Compost						
5	Apg	8	A	0		L	12	10 YR 4/2	mo	co	gr	fr	0%	5% 7.5YR 5/6, m sm 2% 10YR 5/6, m sm
	BAg	15	A	0		C	35	10YR 5/2	mo	m	sbk	fr	5% 10 YR 5/1, f sm	20% 10YR 6/6, f sm 3% 2.5 YR 5/8, p
	Btg	30+	-	0		C	50	10 YR 5/2	st	m	sbk	fi	7% 10YR 5/1, f sm	20% 7.5 YR 5/8, m sm 10 % 10YR 7/4, f sm
8	Apg	6	A	0	-	CL	30	10 YR 4/2	wk	m	gr	fr		2% 10YR 5/6
	BAg	14	A	0	-	CL	39	10YR 5/2	wk	m	sbk	fi	2% 10YR 6/1	5% 10YR 4/6 2% 2.5YR 4/8
	Btg	30+		0	-	C	50	10YR 6/1	wk	co	sbk	vfi	5% 10YR 7/1	7% 7.5YR 5/8
11	Ap	5	C	1		SiL	8	10YR 4/2	mo	m	gr	fr	0%	0%
	Apg	11	A	5		SiL	15	10YR 4/2	wk	m	sbk	fr	0%	2% 10YR 5/8, f sm
	Btg	30+		5		C	45	2.5Y 5/2	mo	th	pl	efi	4% 10YR 6/1	5% 2.5YR 4/8 5% N2.5, Mn

														15% 5YR 5/8
20	Ap	7	C	1	r	SiL	20	10YR 4/2	mo	m	sbk	fi	0%	1% 10YR 6/6, f sm
	BAg	15	A	0	-	SiL	24	10YR 5/2	wk	m	sbk	fi	0%	8% 10YR 6/6
														2% 10YR 5/8
														2% 5YR 4/6
														2% 2.5Y 6/8
	Btg	30+	-	0	-	C	45	2.5Y 6/2	st	th	pl	efi	2% 7.5YR 6/1, f rc	9% 5YR 4/6
														6% 10YR 6/8
														3% N2.5, Mn

Treatment 2: 56 Mg ha^{-1} Compost

6	Ap	6	A	0		L	18	10YR 4/2	wk-mo	m	gr	vfr	0%	0%
	Btg1	17	C	0		CL	34	10YR 5/2	mo	m	sbk	fi	3% 10YR 7/1	2% 10YR 4/8
														12% 10YR 5/8
	Btg2	30+		0		C	40	2.5Y 6/1	wk	co	sbk	vfi	6% 10YR 7/1	4% 5YR 4/6
														8% 7/5YR 5/8
10	Ap1	4	C	0	-	SiL	12	10YR 4/2	mo	m	gr			
	Ap2	11	A	0	-	SiL	17	10YR 5/2	mo	m	gr			
	BAg	17	A	0	-	L	25	10YR 5/2	wk	m	sbk		2% 10YR 6/1	10% 10YR 4/6
	Btg	30+	-	0	-	C	45	10YR 6/1	mo	m	sbk			5% 10YR 5/8
														25% 10YR 6/6

14	Ap	5	A	0		SiL	18	10YR 3/2					0%	0%
	BAg	12	A	2	r	CL	30	10YR 4/2	wk	m	sbk		2% 10YR 5/2	2% 7.5YR 5/8
														4% 10YR 5/8
	Btg	30+	-	2	r	C	45	10YR 5/2	mo	th	pl		4% 10YR 6/1	5% 10YR 4/8
														8% 10YR 5/8
														12% 10YR 7/8
18	Apg	10	C	1	r	SiL	12	10YR 4/2	mo	m	sbk	fr	2% 2.5Y 6/2	3% 10YR 5/3
	BAg	19	C	5	r	SiL	20	10YR 5/2	mo	m	sbk	fr	3% 10YR 6/1	6% 10YR 5/3
	Btg	30+	-	0	-	C	45	2.5Y 5/2	st	th	pl	vfi	2% 10YR 6/1, sm	3% 10YR 4/8
														10% 7.5YR 5/8

Treatment 3: 112 Mg ha^{-1} Compost

4	Ap	11	A	0		SiL	10	10YR 3/2	mo	f	gr+sbk	fr	3% 10YR 6/2, f sm	2% 10YR 3/4, f rc
	BAg	18	A	1		SiL	10	2.5Y 5/2	wk	m	gr+sbk	fr	15% 2.5Y 6/2, m sm	2% 10YR 6/8, f sm
	Btg	30+		1%	r	C	41	10YR 5/1	mo	m	sbk	vfi	10% 2.5Y 6/2, m sm	2% 5YR 5/8, f sm
9	Ap	10	C	1	a	SiL	10	10YR 3/2	mo	m-co	gr			1%, 7.5YR 4/6
	BAg	17	A	1	r	SiL	24	10YR 6/2	wk	m	sbk		2% 10YR 7/1	2% 5YR 3/4
														15% 7.5YR 5/8
	Btg	30+		0	-	C	45	10YR 6/1	mo	th	pl-sbk			2% 10YR 7/8
														20% 7.5 YR 5/8

12	Ap	11	A			SiL	14	10YR 3/2	mo	m	gr	fr	0%	0%
	BAg	17	A	2	a+r	SiL	22	10YR 4/2	wk	m	sbk	fr	2% 10YR 6/1, f rc	5% 2.5YR 5/8
														10% 10YR 6/8
	Btg	30+	-	0		Clay	45	10YR 5/2	mo	th	pl	vfi	6% 10YR 6/1	3% 2.5YR 5/8
														5% 10YR 6/6
														10% 10YR 5/8
19	Ap	6	C	2	a	SiL	20	10YR 3/2	mo	m	gr	fr	0%	0%
	BAg	13	C	0		CL	28	10YR 4/2	wk	m	sbk	fr	10% 2.5Y 6/1	4% 7.5YR 5/8
														6% 10YR 5/8
	Btg	30+		0		C	45	2.5Y 5/2	mo	th	pl	vfi	10% 2.5Y 6/1	4% 7.5YR 5/8
														6% 10YR 5/8

Treatment 4: 224 Mg ha^{-1} Compost

2	Ap	10	C	1		L	10	10YR 2/2	mo	m	gr	vfr	0%	0%
	Bg	26	A	1		L	16%	10YR 4/2	mo	m	sbk	fr	5% 10YR 7/1	2% 7.5YR 3/4, f sm
														5% N2.5, Mn
														10% 10YR 6/8
	Btg	30+	-	0		C	55	10YR 5/1	mo	m	sbk	fi	0%	5% 7.5YR 3/8
											pl			5% 10YR 5/8
														15% 7.5YR 6/8
3	Ap	11	C	0		L	8	10YR 2/2	mo	m	gr	vfr	0%	0%
	Bg1	20	C	0		L	15	10 YR 5/2	mo	m	sbk	fr	2% 2.5Y 6/2, f sm	2% 5YR 4/6

	Bg2	30+		0		L	15	10YR 5/2	mo	m	sbk	fr	4% 2.5Y 6/2, f sm	4% 10YR 5/6, m sm
														15% 2.5 YR 3/6, f sm+rc
7	Ap	10	A			L	10	10YR 2/1	mo	m	gr	vfr	0%	0%
	BAg	19	C			L	24	10YR 4/2	mo	m	sbk	fi	1% 10YR 7/1	2% 2.5YR 4/6
														8% 10YR 5/8
	Btg	30+	-			CL	36	10YR 5/1	wk		pl-sbk	vfi	2% 10YR 7/1	6% 2.5YR 4/6
														15% 10YR 5/8
17	Ap	12	A	0	-	L	8	10YR 2/1	mo	m	gr	vfr	0%	0%
	BAg	25	A	0	-	SiL	18	2.5Y 5/2	wk	m	sbk	fr	2% 10YR 6/1	5% 10YR 5/8
	Btg	30+	-	0	-	C	45	2.5Y 6/1	st	th	pl	vfi	2% 10YR 6/1	5% 2.5Y 5/8
														15% 10YR 5/8

Treatment 5: 336 Mg ha^{-1} Compost

1	Ap	11				SiL	10	10YR 2/2	st	m	gr		0%	0%
	BAg	23		1		L	24	10YR 4/2	mo	m	sbk		2% 2.5Y 6/3	2% 7.5YR 3/4
														5% 10YR 6/6
	Btg	30+		1		C	50	10YR 5/1	wk	co	sbk		4% 2.5Y 6/3	4% 2.5YR 5/8
														8% 10YR 5/8
13	Ap	10	A	2	a	L	10	10YR 2/2	mo	m	gr	fr	0%	0%
	BAg	21	A	2	r	L	20	10YR 4/2	wk	m	sbk	fr	2% 2.5Y 7/3, m sm	2% 7.5YR 6/4
														3% 10YR 5/6, sm
	Btg	30+	-	2	r	C	45	10YR 5/2	mo	th	pl-sbk	fi	6% 10YR 6/1, sm	5% 2.5YR 4/8

														10% 10YR 5/8
15	Ap	10	A	5	a	SiL/L	10	10YR 3/2	mo	m	gr		0%	0%
	BAg	25	A	5	r	L	18	2.5Y 5/2	wk	m	sbk		2% 2.5Y 5/1	5% 5YR 4/6
														8% 10YR 6/8
	Btg	30+	-	5	r	C	45	2.5Y 5/2	mo	th	pl		2% 2.5Y 5/1	5% 7.5YR 5/8
														5% N2.5, Mn
														20% 10YR 5/8
16	Ap	10	A	2		SiL	10	10YR 2/1	mo	m	gr	fr	0%	0%
	Bg1	23	C	2		SiL	20	10YR 4/2	mo	m	sbk	fr	1% 10YR 5/1 sm	4% 5YR 4/6, rc
													5% N4 medium sm	5% 10YR 5/8, sm
	Bg2	30+	-	5	r	SiL	15	10YR 4/2	wk		pl-sbk	fr	2% 10YR 5/1 sm	3% 10YR 5/8
														4% 7.5YR 5/6
														7% 7.5YR 5/8

Table D2. Soil descriptions at CCW-Wet. Descriptions were made on November 5 and 6, 2016.

	Horizon			Rock Fragments		Texture		Matrix Color	Structure				Redox Features	
Plot	Name	Lower depth (cm)	Boundary	%	Shape	USDA Class	Clay %	Hue value/chroma	Grade	Size	Shape	Moist Cons.	Depletions	Concentrations

Treatment 1: 0 Mg ha^{-1} Compost

3	Apg	4	A	0		L	10	10 YR 4/2	wk	m	gr	vfr	0%	3% 7.5YR 4/6
	Bg	18	C	3	a	CL	36	10 YR 5/1	wk	m	sbk	fi	0%	3% 5YR 3/4
														3% 2.5Y 7/4
														10% 10YR 5/8
	Btg	30+		0		C	46	10YR 6/1	wk+mo	vth+m	pl-sbk	vfi	0%	2% 5YR 3/4, rc
									(wk vth pl breaking to mo m sbk)					3% 5YR 5/8
														10% 2.5Y 7/4
														20% 10YR 5/8
9	Apg	2	C	0		L	18	10YR 4/2	wk	m	gr	fr	0%	2% 10YR 4/6
	Bg1	8	C	2	r	L	25	10YR 5/2	wk-mo	m	gr+sbk	fi		3% 10YR 4/3
									(wk m gr, mo m sbk)					5% 7.5YR 4/6
	Bg2	20	C	2		L	20	10YR 4/2	mo	m	gr	fi		2% 10YR 6/8
														3% 7.5YR 5/8
	Btg	30+		1	r	C	50	10YR 6/1	mo	th-vth	pl	vfi	5% 2.5Y 7/1	2% N2.5
														3% 7.5YR 5/8
														10% 10YR 6/8
14	Ap	4	A	0		L	15	10YR 5/2	wk	m	gr	fr	0%	0%
	Btg1	19	C	1	r	CL	34	10YR 5/2	wk	m	sbk	fr	6% 10YR 5/1	3% N2.5
														3% 10YR 4/6
	Btg2	30+		0		C	50	10YR 5/1	wk	th	pl	vfi	2% 5Y 6/2	2% 10YR 4/6
														8% N2.5

														8% 10YR 6/8
														10% 5YR 5/8
16	Apg	3	A	0		L	18	10YR 5/2	mo	m	gr	vfr	0%	2% 10YR 4/6, sm+rc
	BA g	19	C	0		L	25	10YR 6/2	mo m gr, wk m sbk			fr	5% 2.5Y 6/1	2% N2.5
														8% 7.5YR 4/6, sm+rc
	Btg	30+		3%	r	C	41	10YR 6/1	wk	th	pl	fi	10% 2.5Y 6/1	2% 5YR 5/8
														3% 7.5YR 5/8
														5% N2.5, Mn
														18% 10YR 6/8

Treatment 2: 56 Mg ha^{-1} Compost

4	Apg	5	A	2		L	20	10YR 4/1	mo	m	gr	fr		2% 5YR 6/8
	Btg1	24		2		C	41	10YR 5/1	wk	m	sbk	vfi		2% 5YR 6/8
														5% 10YR 3/2
														40% 10YR 5/8
	Btg2	30+		0		C	49	10YR 5/1	wk	vth	pl	vfi	3% 2.5Y 7/1	2% 5YR 6/8
														10% 10YR 3/2
														20% 10YR 5/8
7	Ap	6	A	0		SiL	14	10YR 4/2	mo	m	gr	fr	0%	0%
	Bg	19	A	0		SiL	21	10YR 5/2	wk	m	sbk	fr-fi	4% 10YR 5/1, sm	3% 10YR 3/4
														10% 10YR 6/8

	Btg	30+			C	47	10YR 5/1	mo vth pl breaking to mo m sbk			fi	10% 10YR 6/1, sm	4% 10YR 3/4
													5% N2.5, Mn
													15% 5YR 6/8
													20% 10YR 6/8
12	Apg	9	A	0	L	20%	10YR 4/1	mo		gr+sbk	fr	4% 10YR 6/2	7% 5YR 4/4, sm+rc
	Btg1	19	C	0	CL	35%	10YR 6/1	mo	m	sbk	fi	14% 2.5Y 7/1	2% 5YR 5/6
													5% 7.5YR 4/6
													20% 10YR 6/6
	Btg2	30+			C	40	10YR 6/1	st	vth	pl	vfi	17% 2.5Y 7/1	2% 2.5N, Mn
													5% 5YR 5/6
													12% 5YR 5/8
													25% 10YR 6/8
19	Ap	8	A	0	L	16	10YR 4/2	mo	m	gr	fr	0%	0%
	Bg	16	A	0	L	25	10YR 5/2	wk	m	sbk	fr	0%	2% 7.5YR 4/6
													4% N2.5
	Btg	30+		0	C	55	7.5YR 5/1	mo	vth	pl	vfi	5% 10YR 7/1	8% 5YR 5/8
													12% 10YR 6/8

<u>Treatment 3: 112 Mg ha^{-1} Compost</u>

1	Apg	10	C		SiL	18	10YR 4/2	wk	m	gr+sbk	vfr	0%	2% 10YR 4/6 rc
	Btg1	21	C		CL	36	10YR 5/1	mo	th-vth	pl	fi		3% 5YR 5/8, sm

	Btg2	30+				C	42	10YR 5/1	st	vth	pl	vfi	7% 10YR 7/2	5% 2.5Y 7/6, sm+rc 15% 7.5YR 5/8, sm 3% 5YR 5/8, sm+rc 30% 7.5YR 6/8, sm
8	Ap	9		2		SiL	15	10YR 4/2	wk	m	gr	fr	0%	2% 10YR 3/4
	Btg1	18		5		CL	34	10YR 5/2	wk	m	sbk	fi	3% 2.5Y 5/1	5% 7.5YR 5/8, sm 6% 7.5YR 3/4, sm+rc
	Btg2	30+				C	49	10YR 6/1	mo	vth	pl	vfi	5% 2.5Y 5/1	2% 7.5YR 3/4, rc
														3% 5YR 5/8
														20% 7.5YR 5/8
15	Ap	8	A			L	18	10YR 4/2	mo	m	gr	fr	0%	1% 5YR 5/8
														4% 7.5YR 4/6
	BAg	24	A	2	a	L	26	10YR 5/2	mo	m	sbk	fi	3% 2.5Y 6/1	2% 7.5YR 4/6
														2% 10YR 6/6
														2% 5YR 5/8 5% N2.5, Mn
	Btg	30+				C	48	10YR 5/1	mo	vth	pl	vfi		8% 5YR 5/8
														8% N2.5, Mn
														10% 10YR 6/6

18	Ap	9	A	1	r	SiL	12	7.5 YR 2.5/1	mo	m	gr	vfr	0%	0%
	Bg	19	A	1	r	L	25	10YR 5/2	wk	m	sbk	fr	3% 2.5Y 6/1	2% 5YR 4/6
														7% 10YR 4/6
	Btg	30+				C	50	10YR 6/1	mo	vth	pl	vfi	5% 10Y 7/1	9% 5YR 5/8
														10% 10YR 6/8

<u>Treatment 4: 224 Mg ha^{-1} Compost</u>

5	Ap	12	A			SiL	10	7.5YR 2.5/1	mo	m	gr	vfr	0%	0%
	Btg1	22	A			C	40	10YR 5/1	wk	m	sbk	fi	2% 2.5Y 7/1	3% 5YR 5/8
														3% 7.5YR 5/8
	Btg2	30+				C	45	10YR 6/1	mo	th	pl	vfi	4% 2.5Y 7/1	3% 5YR 5/8
														5% 7.5YR 5/8
														10% 10YR 5/8
6	Ap	9	A	2	r	SiL	12	10YR 2/2	mo	m	gr	vfr	0%	0%
	Btg1	21	C			CL	37	2.5Y 5/1	wk	m	sbk	fi	0%	7% 5YR 5/8, sm+rc
														12% 10YR 6/8, sm
	Btg2	30+				C	42	2.5Y 6/1	st	m	sbk	fi	4% 2.5Y 7/1, sm	14% 5YR 5/8, sm
									wk	m	pl	fi		14% 10YR 6/8, sm
13	Ap	11	A			SiL	12	10YR 2/2	mo	m	gr	vfr		2% 7.5YR 5/6, rc
	Btg1	25	A	1	a	CL	30	10YR 5/2	wk	m	sbk	fr	8% 2.5Y 6/2	10% 5YR 5/6, sm+rc
	Btg2	30+		1	r	C	48	10YR 5/1	mo	very thick	pl	vfi	10% 2.5Y 6/2	3% 10YR 5/8

									mo	medium	sbk	vfi		4% N2.5, Mn
														10% 10YR 6/8
17	Ap	8	A			SiL	11	10YR 3/2	wk	fine	gr		0%	0%
	Bg	22	C	2	a	L	23	10YR 5/2	wk	medium	sbk		2% 2.5Y 6/2	3% 5YR 5/8
														4% 10YR 3/6
	Btg	30+		3	r	C	41	10YR 6/1	wk	thick	pl		5% 2.5Y 7/3	3% 2.5N, Mn
														8% 5YR 5/8
														20% 10YR 6/8

Treatment 5: 336 Mg ha^{-1} Compost

2	Ap	12	C			SiL	11	10YR 2/2	mo	medium	gr	vfr	0%	0%
	BA g	19	A			L	18	10YR 4/2	mo	medium	gr	fr	0%	1% 5YR 5/8, sm 7% 20YR 5/8, sm+rc
	Btg	30+				C	41	10YR 5/1	wk	medium	sbk	fi	0%	2% 5YR 5/8
														3% N2.5, Mn
														7% 5YR 3/4
														20% 10YR 5/8
10	Ap	11	A			SiL	15	7.5YR 2.5/1	mo	medium	gr	vfr	0%	0%
	Btg1	22	A	1	r	CL	36	10YR 5/2	wk	medium	sbk	fi	2% 10YR 5/1, sm	2% 7.5YR 5/8
														3% 10YR 6/8
	Btg2	30+				C	42	10YR 6/1	wk	very thick	pl	fi	10% 2.5Y 7/3	3% 5YR 5/8

														3% N2.5, Mn
														4% 7.5YR 3/3
														10% 10YR 6/8
11	Ap	11	A	2	r	SiL	10	10YR 2/1	mo	medium	gr	vfr	0%	0%
	Btg1	25	C			CL	28	10YR 6/2	wk	medium	gr	fr	2% 10YR 6/1, p	1% 5YR 6/8, rc
									wk	medium	sbk	fr		2% 10YR 6/8, sm
														7% 10YR 4/6, sm+rc
	Btg2	30+				C	45	10YR 6/1	mo	vth+m	pl-sbk	vfi		2% 5YR 6/8, sm
														4% 2.5Y 7/4
														5% N2.5, Mn
														10% 10YR 4/6, sm+rc
20	Ap	10	A			SiL	12	10YR 2/2	mo	m	gr	vfr	0%	0%
	Bg	22	A			L	25	10YR 5/2	mo	m	sbk	fr	1% 2.5Y 6/1	1% 2.5Y 6/4
														2% 10YR 4/6
														2% N2.5, Mn
	Btg	30+				C	50	10YR 6/2	mo	vth+m	pl-sbk	fi	2% 2.5Y 6/1	2% N2.5
														5% 10YR 6/8
														5% 5YR 5/8

Appendix E. Wetland Vegetation Dominance Tests

Table E1. Percent of dominant wetland species by strata at CCW-Dry. A COE 50/20 dominance test was used. Data collected by Sara Klopf June, 2016.

Compost	Plot	Herbaceous	Sapling	Overall	Hydrophytic? (Y/N)
Mg ha^{-1}		----------------- % -----------------			
0	5	100.0	100.0	100.0	Y
	8	75.0	100.0	83.3	Y
	11	50.0	100.0	75.0	N
	20	100.0	100.0	100.0	Y
56	6	83.3	100.0	87.5	Y
	10	100.0	100.0	100.0	Y
	14	100.0	100.0	100.0	Y
	18	0.0	100.0	66.7	Y
112	4	66.7	100.0	80.0	Y
	9	50.0	100.0	75.0	Y
	12	50.0	100.0	75.0	N
	19	100.0	100.0	100.0	Y
224	2	50.0	0.0	50.0	N
	3	50.0	100.0	75.0	N
	7	33.3	100.0	60.0	N
	17	33.3	100.0	60.0	N
336	1	50.0	100.0	75.0	N
	13	0.0	100.0	50.0	N
	15	100.0	100.0	100.0	Y
	16	100.0	100.0	100.0	Y
Ext. Ref.	DR1	0.0	100.0	33.3	N
	DR2	100.0	100.0	100.0	Y
	DR3	50.0	100.0	80.0	N
	DR4	100.0	100.0	100.0	Y

Table E2. Percent of dominant wetland species by strata at CCW-Wet. A COE 50/20 dominance test was used. Data collected by Sara Klopf June, 2016.

Compost	Plot	Herbaceous	Sapling	Overall	Hydrophytic? (Y/N)
Mg ha^{-1}		----------------- % -----------------			
0	3	100.0	100.0	100.0	Y
	9	100.0	100.0	100.0	Y
	14	100.0	100.0	100.0	Y
	16	100.0	100.0	100.0	Y
56	4	100.0	100.0	100.0	Y
	7	100.0	100.0	100.0	Y
	12	100.0	100.0	100.0	Y
	19	100.0	100.0	100.0	Y
112	1	80.0	100.0	85.7	Y
	8	100.0	100.0	100.0	Y
	15	83.3	100.0	85.7	Y
	18	100.0	100.0	100.0	Y
224	5	100.0	100.0	100.0	Y
	6	85.7	100.0	88.9	Y
	13	100.0	100.0	100.0	Y
	17	50.0	100.0	75.0	Y
336	2	100.0	100.0	100.0	Y
	10	100.0	100.0	100.0	Y
	11	50.0	100.0	75.0	Y
	20	100.0	100.0	100.0	Y
Ext. Ref.	WR1	100.0	100.0	100.0	Y
	WR2	100.0	100.0	100.0	Y
	WR3	100.0	100.0	100.0	Y
	WR4	100.0	100.0	100.0	Y

Appendix F. External Reference Soil Properties at CCW

Table F1. Soil Properties in two plots by horizon at CCW-Dry and CCW-Wet. There were two bulk density samples per horizon that were combined for carbon analysis.

Plot	Horizon	Mean BD	Carbon	Nitrogen	C:N
		g cm^{-3}	%		
		---------------------------- CCW-Dry	----------------------------		
DR1	Ap	1.12	2.62	0.19	14.02
DR1	BA	1.49	1.58	0.12	13.73
DR1	Btg	1.56	0.48	0.06	8.69
DR3	Ap	1.24	2.85	0.21	13.68
DR3	BA	1.58	1.08	0.08	14.15
DR3	Btg	1.81	0.30	0.04	7.57
		---------------------------- CCW-Wet	----------------------------		
WR1	Ap	1.18	1.93	0.15	12.83
WR1	BA	1.51	1.10	0.07	15.69
WR1	Btg	1.38	0.31	0.05	6.04
WR4	Ap	1.35	1.62	0.14	11.48
WR4	BA	1.58	1.36	0.07	20.13
WR4	Btg	1.45	0.32	0.07	4.70