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Effects of amendments and microtopography on created tidal freshwater wetland soil morphology and carbon

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Abstract

Created wetlands used to mitigate impacts to natural wetlands often have lower organic matter, less microtopography, fewer hydric soil field indicators (HSFIs), and higher bulk density (BD) than natural wetlands. Organic matter amendments may improve soil properties soon after wetland construction, but long-term effects are seldom studied. This study investigated changes with time in soil properties of a sandy freshwater tidal created wetland in the Coastal Plain of Virginia. During construction in 2003/2004, five compost and topsoil treatments were applied, along with pit–mound microtopography. Soil descriptions were made in 2005, 2007, and 2015; samples were taken in 2006 and 2015. Four years after wetland construction, 69% of sandy plots met one or more HSFIs (S5, S6), and 62% of loamy plots met an HSFI (F3). Plots with loamy topsoil additions exhibited greater horizon and structure development, HSFI stability, greater soil mass C (0–30 cm), and higher soil C accumulation. Average soil C accumulation to 30 cm was 2.86 Mg ha^{-1} yr^{-1} in topsoil plots. With time, soils became darker (lower value, chroma) and higher in A horizon total C, and grayer (lower chroma) in C horizons, regardless of treatment. In 2015, microtopographic pits had lower color value (2.4), chroma (1.9), BD (0.87 g cm^{-3}), and higher total C (2.39%) than mounds. We recommend adding pit and mound microtopography to created wetlands for increasing diversity of habitat. Further study is needed to see if topsoil and compost amendments improve long-term plant community development in sandy created wetlands and in other wetland types.

1 | INTRODUCTION

Development, road building, agricultural, and forestry land uses have reduced the extent of U.S. wetlands by >50% (Dahl, 1990). Restoration and wetland creation have been used to offset losses since the 1980s (Allen & Feddema, 1996; Atkinson, Perry, Smith, & Cairns Jr, 1993; Brown & Lant, 1999; Mitsch, 1992). The least successful type of wetland impact mitigation is often the creation of new wetlands from former uplands. 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 C (TC) (Bishel-Machung, Brooks, Yates, & Hoover, 1996; Fajardo, 2006; Stolt et al., 2000; Whittecar & Daniels, 1999), compaction (Bishel-Machung et al., 1996; Campbell, Cole, & Brooks, 2002), limited rooting volume (Daniels et al., 2005), and inappropriate hydrology (Cole, 2017).

Many studies have shown that adding organic matter (OM) during wetland construction improves wetland soil properties within the first few years. Organic matter amendments

Abbreviations: BD, bulk density; HSFI, hydric soil field indicator; OC, organic carbon; OM, organic matter; TC, total carbon; TN, total nitrogen; WWE, Weanack Wetland Experiment.

may include leaf and lawn compost, food processing waste, and forest products (Stauffer & Brooks, 1997). Adding organic amendments can increase soil aggregation, porosity, water holding capacity, and soil moisture content (Bruland & Richardson, 2004; Stauffer & Brooks, 1997). Organic matter additions can also decrease soil BD, increase the rate of reduction of Fe in anaerobic soils, and restore other soil properties such as low redox potential (Eh) needed for hydrophytic plants to compete and survive (Bruland, Richardson, & Daniels, 2009). The standard for jurisdictional wetland hydrology is 14 consecutive days of saturation in the upper 12 inches (30.5 cm) of the soil (U.S. Army Corps of Engineers, 2010), although under ideal conditions reduction of Fe may take place faster. Without the addition of OM, saturation times of up to 96 h may still not be sufficient to lead to the reduction of Fe and Mn (Meek, Mackenzie, & Grass, 1968). Adding OM to a silty clay soil increased the amount of Fe and Mn in the soil solution in the upper 10 cm (Meek et al., 1968) in that same study.

Hydric soils are identified in the field by hydric soil field indicators (HSFIs) (Vasilas, Hurt, & Berkowitz, 2017), which use soil morphological characteristics that are associated only with wetland soils. These morphological properties are caused by the accumulation or loss of Fe, Mn, S, or C compounds. The indicator F3 Depleted Matrix for fine-textured soils was documented forming within 5 yr of wetland creation in a silty clay loam marsh in Illinois after continuous flooding during the growing season (Vepraskas, Richardson, Tandarich, & Teets, 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, Comerford, & Brown, 1997; Robinette, Rabenhorst, & Vasilas, 2004; Rossi & Rabenhorst, 2015). It is unclear from previous studies whether adding loamy topsoil and/or compost to a created sandy wetland will increase the formation rate and number of redox features and HSFIs. No published studies have shown HSFIs forming <5 yr after wetland construction. Younger wetlands have had fewer growing seasons for surface flow events and plant community root and litter inputs that are the source of OM accumulations and soil C (Ballantine & Schneider, 2009). Hossler and Bouchard (2010) found that created depressional, palustrine wetlands had fewer macroaggregates, more silt and clay, and higher BD, and they concluded that it may take as long as 300 yr to accumulate the same C in the upper 0–5 cm as a similar natural wetland. The time to equivalence for BD was estimated to be 70 yr, and for organic C (OC) it was 400 yr. Wolf, Ahn, & Noe (2011) found that non-tidal freshwater created wetlands 3–4 yr old had lower gravimetric moisture, OC, and TN and higher BD than created wetlands that were 7–10 yr old.

Seasonally saturated wetlands and forests commonly contain small or large irregular changes in local surface elevation (microtopography) that may develop from sediment accumulation, erosion, tree fall, or animal activity (Bruland & Richardson, 2005). In wetland soils, microtopography resulting from tree falls creates pits that contain shallow water for longer than the rest of the surface along with adjacent mounds that are better aerated (i.e., less frequently saturated) and more elevated above the water table. This presence of adjacent saturated and unsaturated zones increases biodiversity by increasing the number of plant species and associated habitat values that can survive in the wetland (Bruland & Richardson, 2005; Pennington & Walters, 2006; Roy, Bernier, Lamondon, & Ruel, 1999; Titus, 1990; Vivian-Smith, 1997). The inclusion of saturated and unsaturated zones in wetlands affects biogeochemical cycling of nutrients, including N_2 fixation and Fe and Al transformations and adsorption (Darke & Walbridge, 2000; Reddy, Patrick, & Broadbent, 1984). Microtopography also creates local heterogeneity in soil nutrient content, pH, and moisture (Beatty, 1984; Bledsoe & Shear, 2000; Paratley & Fahey, 1986). Constructed wetlands typically do not contain microtopography due to extensive grading, construction designs that limit infiltration losses, and the absence of large trees subject to windthrow (Daniels & Whittecar, 2004; Stolt et al., 2000).

Dickinson (2007) and Pietrzykowski, Daniels, & Koropchak (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, and lower root biomass than bald cypress growing on mounds or level areas (Dickinson, 2007). After the 10th growing season, cypress that were growing in pits were more likely to be in dominant and co-dominant ecological crown positions. Tree height, diameter at breast height, diameter at 10 cm, and basal trunk swelling of bald cypress trees were also greater in pits (Pietrzykowski et al., 2015). These results suggested that installed microtopography (particularly pits) directly benefitted cypress growth.

Overall, previous research suggests that topsoil and OM amendments may help created and restored wetlands reach

Core Ideas

- Soil redoximorphic features formed within 2 yr after wetland construction.
- Hydric soil field indicators formed within 4 yr after wetland construction.
- Loamy topsoil amendments led to HSFI stability and greater soil mass C after 12 yr.
- The wetland had a mean soil C accumulation rate of 2.0 Mg ha^{-1} yr^{-1} over 12 yr.

the properties of natural wetlands in less time than when no amendments are used during wetland creation and soil reconstruction. 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 published literature on long-term effects of compost and topsoil amendments on created wetland soil properties. Microtopography also strongly affects local variability in soil physical and chemical properties and processes, but the long-term influence on differential soil properties has not been studied in created wetlands. 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 & Daniels, 1999). Therefore, the objective of this study was to determine changes in soil properties (e.g., morphology, BD, OC, mass C, TN, plant-available nutrient content) with time (>10 yr) due to topsoil and compost additions in a tidal freshwater created forested wetland.

2 | MATERIALS AND METHODS

2.1 | Site description and experimental design

The Weanack Wetland Mitigation Site is an off-site compensation created wetland located in Charles City County, Virginia, at 37.330922 N, 77.265518 W (Figure 1a). The 2.74-ha tidal freshwater wetland includes emergent, shrub-scrub, and forested wetland zones. The wetland is on the James River floodplain in the Virginia Coastal Plain in MLRA 133A of Land Resource Region P (USDA-NRCS, 2006). The Weanack Wetland Experiment (WWE) is 0.24 ha located within the forested wetland component and comprises 21 experimental 6.1- by 6.1-m plots. 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). The dredge materials were placed in the 1950s–1970s by the U.S. Army Corps of Engineers over tidal mud flats and emergent wetlands and were about 95% medium sand with readily visible but faint Fe-oxide coatings. The pretreatment (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).

The site was partially excavated down to a projected maximum seasonal high tide elevation in late 2003 and was approximately 1.01 to 1.13 m above mean low tide. The site is periodically inundated during the winter and during large storms, but water is rarely above the soil surface during the growing season. Well readings from 2005 confirmed that the wetland's hydrology was similar to local tidal freshwater swamps hydrologically connected to the James River and that the site met Corps of Engineers and Virginia Department of Environmental Quality requirements for jurisdictional wetland hydrology (Vanasse Hangen Brustlin, 2005). The poorly drained soil within the experiment area at WWE is not in an established series 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, personal communication).

The experiment contains four treatments with four replicates each, along with a control with five replications (Figure 1b). Plots in Treatments 4 and 5 were undercut by 15 cm and then received 15 cm of stockpiled Pamunkey (Typic Hapludalf) soil on 22 Oct. 2003 (Dickinson, 2007; Soil Survey Staff, 2014a). The topsoil applied was dominantly a loamy A horizon stockpiled by nearby sand mining operations, with some textural variation (Dickinson, 2007). Compost (wood waste based) treatments were applied volumetrically on 27 Oct. 2003 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 (dry) of 12.61%, and C/N ratio 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 disked to 15 cm after all treatments were applied. Microtopography pits and mounds were installed in March 2004. Each plot contains one 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. Compost was added to the pit floor at the same rate as to the bulk plots to compensate for the loss to adjacent mounds.

A minimum of three bald cypress were planted in each plot in March 2004 including one stem in each pit and on each mound. Additional woody wetland species were planted on 23–26 April 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 that included spotted ladysthumb (*Polygonum persicaria* L.), Pennsylvania 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).

2.2 | 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, Wysocki, Benham, & Soil Survey Staff, 2012) in 2005, 2007, and 2015. Soils in 2005

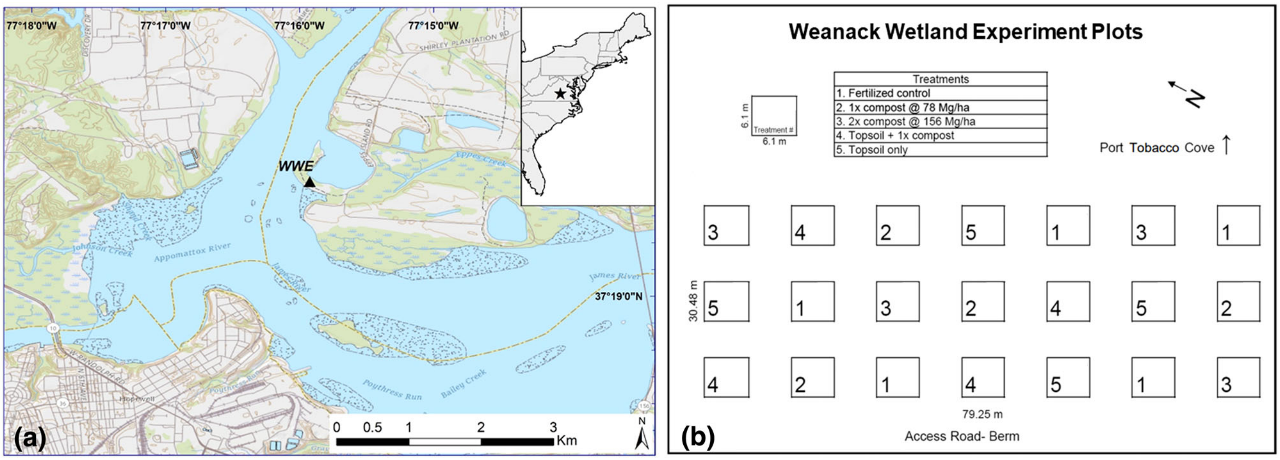

FIGURE 1 (a) Location of the Weanack Wetland Experiment (WWE) on the James River in Charles City County, Virginia (credit: Patricia Donovan, Virginia Tech); (b) WWE research site diagram showing treatments and plot layout (Dickinson, 2007)

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 the 0–3- and 20–25-cm depths and analyzed for particle-size analysis by the pipette method (Gee & Bauder, 1986). In 2015, one sample per horizon per plot was analyzed for texture using the hydrometer method (Gee & Bauder, 1986). Organic matter was removed from the surface horizon samples by adding H_2O_2 and applying heat (Soil Survey Staff, 2014c).

In 2006, 30.5- by 30.5-cm samples were collected from the 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 BD samples were extracted at the top of each horizon in the upper 30 cm within each experimental unit, air dried, and sieved to <2 mm, then combined by horizon for chemical analysis. Rock fragments and coarse OM (roots ≥2 mm) were removed from the samples after air drying; then the samples were corrected for the weight and volume of rocks and roots. There were two to four horizons per plot in 2015. Samples from 2006 and 2015 were tested for TC and TN with an Elementar CN analyzer (Elementar Americas; Nelson & Sommers, 1996). There were no carbonates in the sand at the site or in the topsoil applied, so TC is assumed equal to OC. Organic matter equivalents of soils at the experiment site were estimated by multiplying the OC percentage by 1.724 (Soil Survey Staff, 2014b). The mass C per horizon, using OC and average BD (Bliss & Maursetter, 2010), was determined as

$$C_h = C_s D_{bw} M L \times 100 \quad (1)$$

where C_h is the 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). Mass soil C was determined using samples taken in "level" portions of the plots rather than in pits and mounds. Soil C accumulation in the top 30 cm was estimated by subtracting the original 2003 mass C in added compost from the 2015 mass C to 30 cm and dividing by 12 yr.

Samples from 2006 and 2015 were analyzed for acid-extractable Mn and Fe via a Mehlich-1 extraction (Maguire & Heckendorn, 2011). There was one sample taken per horizon from 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 color value, color chroma, and BD. One sample was taken in each microtopographic location to minimize disturbance. Their BD was estimated by the volumetric core method 3B6a using the probe diameter and layer depth (Soil Survey Staff, 2014c).

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 (instead of repeated measures ANOVA because of a failure to meet assumptions), 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 & Wallis, 1952) followed by the Wilcoxon rank sum test to contrast treatments. Time comparison data were examined by paired *t*-tests ($\alpha = .05$). Delta values (e.g., 2006 value subtracted from

TABLE 1 Moist Munsell soil colors of selected plots in the upper 15 cm immediately after treatment applications in October 2003 (W. Lee Daniels, personal communication)

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

2015 value) were used to test if the differences in parameters (e.g., increase in OC) varied by treatment. A paired *t*-test was also used to test depth effects in BD, TC, and TN between ^A (A) and ^C, ^Cg, and 2^C (C) horizons. Delta values were then treated as independent variables and tested using the methods above. The statistical software JMP (SAS Institute) was used, and α = .05 for all statistical analyses.

3 | RESULTS

3.1 | Amendment effects

In 2003, immediately after application of treatments, the soils had oxidized matrix colors with a hue of 10YR, value 5–6, and chroma 3–8 (Table 1). There were common (5–10%) black to dark brown organans in plots where compost had been incorporated.

Overall, there was very little soil structure development in 2005, 2 yr after wetland creation and treatment application. In 2005, most plots in Treatments 4 and 5 (topsoil plots) had developed only one ^A horizon ("A horizon") in the loamy topsoil parent material. The underlying horizons were ^C, ^Cg, or 2^C horizons ("C horizons"). However, two out of four plots in topsoil 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 A 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 A horizons and one AC horizon. Five of the A 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 A horizon. About half of the plots (10 out of 21) had developed a Cg horizon with strong gleying.

By 2007, three plots had developed a ^Bg or ^Bw horizon ("B horizon"), all in loamy reapplied topsoil. B horizon formation was determined by the 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 the topsoil 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 much stronger in 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). In 2015, every soil had a thin (approximately 5 cm) A horizon at the surface overlying a C or Cg horizon within the 30-cm depth. Soils that formed in loamy topsoil had either Bg or Bw below the A horizon. By 2015, all plots in Treatments 4 and 5 had at least two horizons (A 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, depending on the color. There was no structure in the sandy-textured B horizons and no evidence of argillan formation. 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 topsoil Treatments 4 and 5) were either A, C, or Cg. Most sandy A 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 subsurface horizon with strong gleying (Bg or Cg horizon). Figure 2 shows an example of a soil "mini-profile" from three different treatments (control, 156 Mg ha^{-1} compost, and topsoil). Over 10 yr, there was more horizon development in loamy horizons than in the sandy horizons.

TABLE 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 Concentration	Redoximorphic features Depletion
	cm				%		
Treatment 1: Control							
^A	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							
^A	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							
^A	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							
^A	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							
^A	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

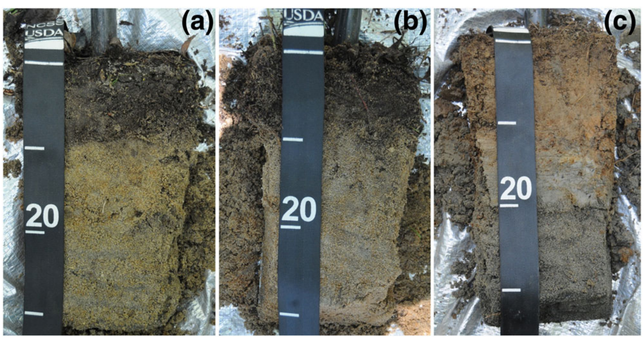

FIGURE 2 Soil mini-profiles taken in 2015 display the presence of a darker A horizon in sandy plots: (a) Plot 5, the control treatment; (b) Plot 21, 156 Mg ha^{-1} of compost applied in 2003; and (c) Plot 19, loamy topsoil applied in 2003. The contact between the loamy topsoil and sand is at 20 cm (photos by Emily Ott)

Immediately after the application of amendments in 2003, the soils in the wetland had oxidized matrix colors with a hue of 10YR, value 5–6, and chroma 3–8 (Table 1). There were black to dark brown compost-stained zones in plots that had compost applied (W. Lee Daniels, personal communication). The brownish yellow dominant color of the sand indicated oxidized Fe^{+3} coatings on sand grains in 2003 that were clearly visible with a hand lens. Redox features were found in every plot by 2005, approximately 1.5 yr after the amendments were added. This is similar to the results of Stolt, Genthner, Daniels, Groover, & Nagle (1998), who found redox features forming within 2 yr in simulated peds amended with OM placed in the subsoil of a created wetland. Interestingly, there were more clearly discernible redox features (concentrations and depletions) present in A and C horizons in 2005 than in 2015.

From 2005 to 2015, average moist ^A horizon values decreased by 1.6 Munsell color units (p < .0001), chroma decreased by 1.4 (p < .0001) units, the quantity of redox concentrations decreased by 12.5% (p < .0001), and obvious redox depletions decreased by 2.5% (p = .0057) (Table 1). With time, distinct ^A horizons formed in all plots by 2015. Figures 3b and 3c show the progression of ^A horizon devel-

FIGURE 3 Representative sandy soil profiles at Weanack Wetland Experiment with time show the development of a dark A horizon: (a) sandy upland dredge in 2003 before excavation (photo by W. 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); and (c) soil plug taken from Plot 5 in 2015 (photo by Emily Ott)

FIGURE 4 Representative loamy soil profiles with time at Weanack Wetland Experiment show a decrease in matrix chroma: (a) soil plug taken from Plot 15, Treatment 4 (topsoil plus 78 Mg ha^{-1} compost) in 2005 (photo by Mike Nester); and (b) soil plug taken from Plot 15 in 2015 (photo by Emily Ott)

opment in a control plot from 2005 to 2015. Figure 4 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.

From 2005 to 2015, average moist C horizon values increased by 0.8 Munsell color units ($p < .0001$), chroma decreased by an average of 1.0 Munsell color unit ($p < .0001$), the quantity of redox concentrations decreased by 1.4% ($p = .0209$), and redox depletions decreased by 1.7% ($p = .0283$). The increase in value and the decreases in chroma, depletions, and concentrations did not vary by treatment. Overall, at 25–30 cm, soils developed higher value and lower chroma colors, and the amount of redox concentrations and depletions decreased (Table 3). These changes resulted in more ^Cg and ^Bg horizons in 2015 than in 2005 ($n = 10$ vs. $n = 21$, respectively).

In 2015, topsoil treatments had a higher A horizon color value than the control treatment ($p = .020$), indicating that the finer particle-sized topsoil was not darkened by C to the same extent as the sandy surface soils (Table 3). The higher OC contents of A horizons resulted in a much lower mean value ($p < .0001$) than C horizons. Redox depletions and concentrations were not found in A horizons of sandy soils, but 0.5% concentrations were found in the loamy topsoil A horizons. Redox depletions and concentrations did not vary by treatment in C horizons. The mean amount of concentrations and 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 yr after excavation and treatment application, none of the plots at WWE met HSFI criteria. Descriptions made in 2005 described redox feature content in qualitative terms (i.e., few, common, many) instead of percentage estimates. Plot 5 in Treatment 1 (control) met indicator S6 if the concentration content was > 10%, but we cannot be sure because the percentage was described as “common,” which could range from 2 to 20%. No other plots in 2005 met a HSFI (Vasilas, 2017; Table 4). In 2007, nine out of 13 sandy plots met HSFIs (S5 and/or S6), and five out of eight loamy plots met a HSFI (F3). From 2007 to 2015, the amount of HSFI S5 decreased from nine to four, and the number of loamy indicators F3 increased from five to eight. The five sandy plots that lacked HSFI stability (i.e., previously met S5 but then failed to qualify in 2015) had a matrix chroma of 3 in the upper 15 cm in 2015, which prevented them from meeting S5. However, loamy soils in Treatments 4 and 5 became more gray (chroma decreased) with time and met more HSFIs in 2015 than in 2007 or 2005.

A horizon silt content increased in Treatments 1, 2, and 3 from 2005 to 2015 ($p < .0001$, $p < .0001$, $p = .0003$ respectively; Table 5) but was not detected in the topsoil treatments (4 and 5). The silt content of C horizons also increased with time in Treatments 1–4 ($p = .0145$, $p = .0057$, $p = .0006$, $p = .0023$), and there was a trend of increased silt in Treatment 5 ($p = .0764$).

The BD levels of the A horizons of the topsoil treatments were higher than the control and compost treatments ($p < .0001$; Figure 5). Soil BD did not vary significantly by treatment across the sandy C horizons ($p = .8009$). None of the BD measured in A or C horizons were presumed to be root limiting (Weil & Brady, 2017).

In A horizons, soil OC increased from 2006 to 2015 by an average of 2.07% ($p < .0001$) (Figure 6). During this period, surface TN also increased by an average of 0.13% ($p < .0001$). These increases in OC and TN did not vary by treatment. Soil OC in the C horizons did not change from 2006 to 2015, but soil TN in C horizons decreased by an average of 0.028%

TABLE 3 Soil color change in surface soil and subsoil from 2005 to 2015. Delta values are means from paired *t*-tests by horizon

Treatment[a]	Value			Chroma			Concentrations			Depletions		
	2005	2015	ΔValue	2005	2015	ΔChroma	2005	2015	ΔConc.	2005	2015	ΔDepl.
							%					
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

[a]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 4 Treatments and plots and their hydric soil indicator status in 2005, 2007, and 2015 (Vasilas et al., 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[a]	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

[a]Depletion percentage described as "common," which is defined as 2 to 20%. HSFI S6 requires ≥ 10% depletions, so we cannot be sure if this met the criteria for S6.

from 2006 to 2015 ($p < .0001$). This decrease did not vary by treatment. No treatment effects were found for OC in A or C horizons by treatment in 2015 (Figure 6). There were also no treatment effects on TN in A horizons (Figure 6). As expected, both TC and TN were much higher in A horizons than C horizons in all treatments ($p < .0001$, $p < .0001$, respectively) but did not vary by treatment.

Soil mass C in 2015 varied by horizon ($p < .0001$) with A and B horizons having greater mass C than C horizons (Table 6) as expected. Soil mass C did not vary by treatment in A, B, or C horizons. There was an average of 13.67 Mg C ha^{-1} in A horizons, 15.24 Mg C ha^{-1} in B horizons, and 3.64 Mg C ha^{-1} in C horizons. However, total soil mass C from 0 to 30 cm did vary by treatment ($p = .0129$) (Table 6). Plots with loamy topsoil had higher mass C than the control (41.28 and 32.32 Mg ha^{-1} in Treatments 4 and 5, respectively, vs. 20.24 Mg ha^{-1} in the control). When accounting for the mass C added in compost in 2003, C accumulation per year in the top 30 cm was higher in the topsoil treatments than in Treatment 3 (Table 6). The fine texture of the loamy topsoil retained more mass C in the upper 30 cm than the sandy treatment plots. Thus, it is interesting to note that the initial compost applications did not have a longer term 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 have long-term effects on mass C, but these higher rates may not be feasible or economical to apply.

In 2015, there was also more extractable Mn in C horizons of the topsoil treatments than in the control, presumably due to higher initial Mn levels in the imported topsoil (Table 7). Differences between means of A horizon Mn and Fe were difficult to determine due to low sample size and unequal variances.

TABLE 5 Mean soil textures in surface A 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)

Treatment[a]	Depth	2006				2015			
		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

[a]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.

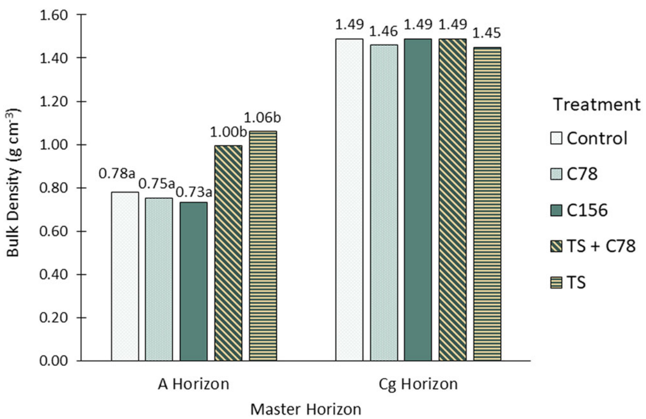

FIGURE 5 In 2015, average bulk density (BD) across treatments varied significantly by treatment in A horizons (α = .05). Sand-derived A horizons had lower BD than A horizons in loam. There was no difference across Cg horizons. Treatment symbols: C78 = compost at 78 Mg ha^{-1}; C156 = compost at 156 Mg ha^{-1}; TS + C78 = topsoil plus 78 Mg ha^{-1} compost; TS = topsoil only

From 2006 to 2015, soil pH decreased ($p < .0001$) and Mn increased ($p < .0001$), ($p < .0018$; Table 8). These changes occurred relatively uniformly across plots and were not significantly affected by treatment.

From 2006 to 2015 in C horizons, there was a decrease in soil pH ($p < .001$), Zn ($p = .0296$), Mn ($p = .0145$), Cu ($p = .0003$), and Fe ($p = .0024$; Table 8). These decreases did not vary by treatment. Soil P, Ca, and Mg in C horizons also did not change between 2006 and 2015, but soil K decreased ($p = .0004$). The means varied slightly by treatment ($p = 0.352$), with Treatment 4 losing more K with time than Treatment 2 ($p = .0294$).

3.2 | Microtopographic effects

All mineral soil surface layers in pits and mounds were described as ^A horizons (Table 9). The average depth of the ^A horizons was 6.0 cm in pits and 4.8 cm on mounds. 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 due to the presence of bald cypress trees. Soil pits had significantly lower color value ($p < .0001$) and chroma ($p = .0147$) than mounds in their surface horizons and lower chroma than mounds and level plots in the second horizons ($p < .0001$). Mounds had higher BD than pits ($p = .0010$; Table 9). Organic C varied significantly by microtopographic location, with pits having significantly higher OC and TN than mounds ($p < .0001$ and $p = .0019$; Table 9).

4 | DISCUSSION

Some soils in loamy topsoil treatment plots developed readily observable redox features and ^Bg horizons in 2–4 yr after construction. By 12 yr after construction and treatment application, all loamy soils had at least one delineated B horizon. Horizon development occurred faster in the loamy topsoil due to the finer texture and higher initial Fe and Mn levels that led to redox feature formation and structural development. In sandy horizons (Treatments 1–3 and lower horizons of Treatments 4 and 5), differences in horizonation were distinguished largely based on color in 2005, 2007, and 2015. Even in 2015, 12 yr after treatment applications, there was no significant soil structure formation in sandy layers except in ^A horizons. ^Cg horizons occurred at varying depths across the wetland and with greater frequency in 2007 and 2015

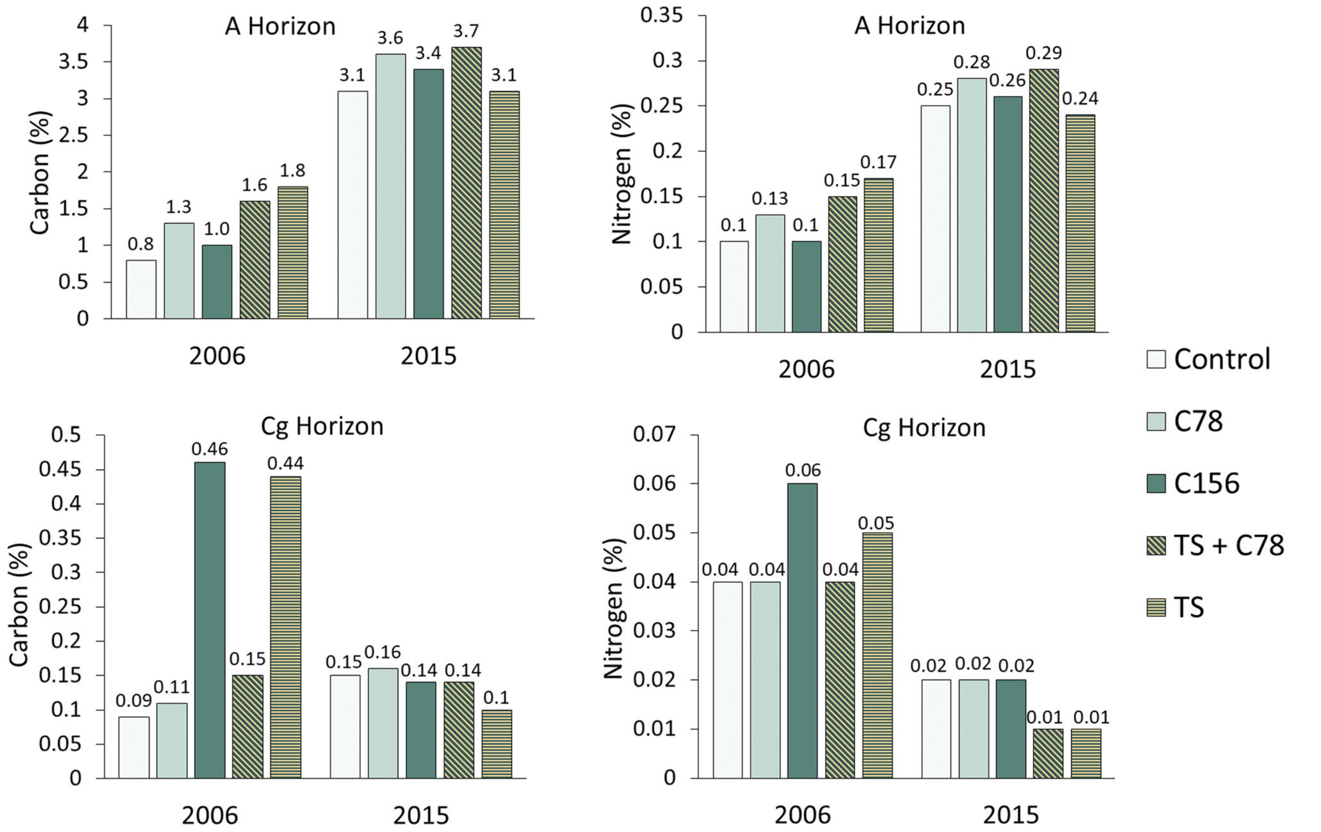

FIGURE 6 Average total organic C (OC) and N (TN) contents in A and C horizons in 2006 and 2015. In A horizons, OC and TN increased with time. These increases did not vary by treatment. In C horizons, OC remained the same with time, while TN decreased independent of treatment. Treatment symbols: C78 = 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

TABLE 6 Mass C added to Weanack Wetland Experiment soils in 2003 vs. mass C to 30 cm retained in soils sampled in 2015

Treatment	Compost C	Soil C	C accumulation
	———Mg ha^{-1}———		Mg ha^{-1} yr^{-1}
Control	0	20.24b	1.68ab
78 Mg ha^{-1} compost	4.96	23.74ab	1.56ab
156 Mg ha^{-1} compost	9.91	21.25ab	0.95b
Topsoil plus 78 Mg ha^{-1} compost	4.96	41.28a	3.03a
Topsoil only[a]	0	32.32a	2.69a

Note. Values followed by different letters are significantly different (α = .05).
[a]TC of topsoil was 0.085% in spring of 2005.

than in 2005. Most plots (19 out of 20) had a horizon with a strongly gleyed matrix within 30 cm by 2007 and again in 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 2005. Mini-profiles were dug in locations not previously sampled, so it is possible that there was some local variation within those plots (i.e., strong gleying might not have occurred uniformly across the plot). The two plots that did not have any horizons with strong gleying in 2015 were located on the slightly drier side of the wetland (Figure 1b; next to an access road and berm), therefore they may have had more aerobic conditions than the other plots. A slight wetness gradient was visually observed, with plots in the north corner being wetter at high tide than those to the south. The compost OM that was originally added in 2003 was decomposed with time into humus and dissolved OC, some of which eluviated into the subsoils and drove microbial reduction, leading to dissolution and leaching of Fe-based redox features over the >10 yr of monitoring. Plant roots also likely contributed to subsoil OC accumulation. Clay in the loamy topsoil treatments promoted subsoil structural development in those plots vs. the very low

TABLE 7 Average extractable Mn and Fe content by treatment in ^A horizons and in C horizons (including ^C, ^Cg, and 2^C) in 2015

Treatment	Nutrient Mn	Fe
	mg kg^{-1}	
	A horizons (approximately 0–5 cm)	
1–Control	35.2	34.7
2–Compost at 78 Mg ha^{-1}	61.6	37.4
3–Compost at 156 Mg ha^{-1}	63.8	53.2
4–Topsoil plus 78 Mg ha^{-1} compost	66.6	43.7
5–Topsoil only	66.4	52.5
	C horizons (approximately 25–30 cm)	
1–Control	5.4a	31.1b
2–Compost at 78 Mg ha^{-1}	9.0ab	52.4a
3–Compost at 156 Mg ha^{-1}	9.0ab	40.6ab
4–Topsoil plus 78 Mg ha^{-1} compost	16.8b	61.2ab
5–Topsoil only	13.0b	51.5ab

Note. Within columns, significant differences are denoted by different letters (α = .05 significance level).

TABLE 8 Change in pH and extractable Mn and Fe content from 2006 to 2015 in ^A horizons (approximately 0–3 cm) and C horizons (25–30 cm)

Nutrient Treatment[a]	Initial pH	Δ pH	Δ Mn	Δ Fe
	mg kg^{-1}			
	A horizons (approximately 0–3 cm)			
1–Control	6.92	−0.89a	26.1a	−46.7a
2–C78	7.07	−1.10a	43.6a	−60.7ab
3–C156	6.81	−0.98a	49.6a	−32.0a
4–TS + C78	6.95	−1.03a	35.5a	−107.4b
5–TS	7.05	−1.21a	22.3a	−62.2ab
	C horizons (approximately 25–30 cm)			
1–Control	6.86	−0.54a	−4.0a	−51.2a
2–C78	6.71	−1.27a	−2.0a	−26.8a
3–C156	6.52	−0.48a	−12.3a	−124.3a
4–TS + C78	6.67	−0.71a	−6.4a	−121.2a
5–TS	6.78	−1.15a	−7.0a	−129.5a

Note. Means followed by letters indicate a significant change from 2006 to 2015 (non-zero delta value). Differences between treatments are denoted by different letters within each column (α = .05)

[a]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.

clay sandy plots. The sandy plots did develop granular soil structure in ^A horizons by 2015 due to higher 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, ^A horizons became darker with time, C horizons developed higher value and lower chroma colors, and redoximorphic concentrations and depletions decreased in both horizons. Over 12 yr, value and chroma decreased (became darker) in the ^A horizons as the originally applied compost decomposed into humus and as local plant litter, roots, and deposited OM accumulated and decomposed into humus. A horizon chroma and value decreased (became less intense and more gray) due to OM additions as well as reduction of oxidized Fe. ^A horizons became uniformly thicker and darker with time but decreases in ^A horizon value and chroma did not vary by treatment (i.e., compost and topsoil did not lead to faster ^A horizon color development than the control). Discernible redox features formed within about 1.5 yr at this wetland (2005) in most plots and remained through 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 across 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 ^A horizons; value increase and chroma decrease in C horizons) did not vary

TABLE 9 Average moist Munsell color, bulk density (BD), total C (TC), and total N (TN) in the surface and average color in second horizons

Location	Surface Value	Chroma	BD	TC	TN	2nd Horizon Value	Chroma
			g cm−3	%			
Mound	3.2a	2.3a	1.05a	2.39a	0.19a	4.7a	3.1a
Pit	2.4b	1.9b	0.87b	3.73b	0.26b	4.5a	2.1b

Note. Within columns, significant differences are denoted by different letters (α = .05 significance level).

by treatment, so the change in soil colors with time was not directly due to compost or topsoil amendments.

By 2015, 12 of the 21 plot descriptions met HSFIs. 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 of 4 or more with chroma of 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 riverine systems may have 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 faint brownish yellow to yellowish brown in color at the time of wetland development, with clearly visible (via a hand lens) light Fe-oxide coatings on the sand grains. The Fe-oxide coatings were reduced and became soluble, moving out of the upper soil soon after the site was excavated and compost was applied. More sandy plots may have met S5 and S6 in 2007 than in 2015 due to the palatable quality of the recently added compost, which led to intense Fe reduction; by 2015, microorganisms had decomposed much of the original compost, and only a more refractory C source remained. The James River drains the Virginia Piedmont and is a likely source of soluble Fe. It is possible that the daily influx of river water may have contributed a small supply of Fe oxides into the system that offset the reduction of Fe in the sandy horizons below the A horizons but above the more permanently saturated Cg horizons. The addition of Fe to the system through flooding may have contributed to the formation of layers with chroma 3 in sandy plots by replenishing oxidized Fe after the intensity of reduction slowed, which disqualified them from meeting S5. It is uncertain whether more of the sandy soils will meet HSFIs with time, except for HSFIs related to OM accumulation or redistribution (e.g., A7 Mucky Mineral, A11 Depleted Below Dark Surface). At this site, it took about 1.5–4 yr to form HSFIs, which is slightly faster than the results of Vepraskas et al. (1999), who found that the F3 Depleted Matrix indicator formed in 4–5 yr.

Topsoil treatments helped maintain more HSFIs with time than the sandy control or compost treatments. 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. Thus, the absence of HSFIs in sandy or loamy created wetlands that are tidally and frequently flooded is not likely due to insufficient time for formation alone. Soils that are low in OC and/or Fe or that form in problem parent materials may take longer to develop HSFIs. At this site, floodwater and tides from the James River likely contributed 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 litter fall 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 used. 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 & Rabenhorst, 2015).

The ^A horizons in Treatments 1–3 (sandy soils) and ^C horizons in Treatments 1–4 increased in clay and silt content with time. Silt was brought into the wetland on periodic tidal influxes and storm flooding events, which explains the increased silt content in A horizons. An increase in silt content from 2005 to 2015 indicates that the site provided the essential sediment trapping function. The limited increase in silt content of C horizons is most likely due to limited eluviation of silt into the subsoil (Bodman & Harradine, 1939; Wright & Foss, 1968).

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

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 (Weil & Brady, 2017). Total C values were almost high enough for mucky-modified textures (Figure 6), leading to the relatively low surface BD values across all plots. At this site, the loamy topsoil plots had higher BD than the sands because of minor grading-related compaction coupled with infilling of finer particles between sand grains during subsequent flooding of the wetland. The sand textures are well sorted with very few fines and are more resistant to compaction and infilling.

After 12 yr, compost amendments did not maintain higher OC or TN content in surface or subsurface soils than treatments without compost amendment in sandy-textured soil horizons. Increases in OC and TN were due to background OM accumulation (e.g., yearly litter deposits and fine root turnover) and not the original treatments. The OC may have increased rapidly in all soils due to the relatively wet overall site conditions and inputs of OC due to litter fall, rooting, and OC deposited by flooding. During the 12 yr studied, there was litter fall and fine root turnover from the forest seedlings, saplings, and tree vegetation with grasses and forbs beneath, which contributed to soil OC across all experimental units. The litter was incorporated into the soil by macro- and microorganisms to form A horizons with time. The periodic flooding events likely contributed suspended OM and might also have contributed finely divided organic-rich sediments and possibly dissolved OC to the wetland, which would contribute to the similarity in OC among treatments. In addition, the extensive disking left the site with favorable soil physical properties. After 12 yr, 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 with other wetlands.

In created wetlands in Virginia, soil mass C (to 1 m) has been reported to range from 47 to 176 Mg C ha^{-1} (Fajardo, 2006), and natural wetlands in the contiguous United States have an average soil mass C of about 720 Mg ha^{-1} (Kern, 1994).

Compost amendments lowered BD and increased TC and TN in the loamy applied topsoil compared with the sandy control treatments, but depending on compost rates applied and parameters evaluated, these differences diminished with 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 yr at the same experimental wetland (Pietrzykowski et al., 2015). Wetlands with drier or more seasonally fluctuating hydrology may have produced different results as well because of the droughtiness of coarse sand textures that are also low in OC and/or in created wetland sites with much drier hydroperiod regimes. Mass C to 30 cm was higher in plots with topsoil added than in compost or control plots (41.28 and 32.32 Mg ha^{-1} in Treatments 4 and 5 vs. 20.24 Mg ha^{-1} in the control). The finer particles of the topsoil retained more OC in the soil profile than the loose sands while limiting gas exchange, leading to higher total mass C. Carbon accumulation per year was higher in topsoil Treatments 4 and 5 (3.03 and 2.69 Mg ha^{-1} yr^{-1}, respectively) than in Treatment 3 (0.95 Mg ha^{-1} yr^{-1}). The results show that as more OC was added, the annual increase in mass C was lower. This implies that equilibrium is being reached in the sandy soils.

Extractable nutrients appeared to vary by treatment in 2015 due to texture and associated differences in mineralogy. The loamy topsoil had a much higher extractable Fe and Mn content than the control due to higher original mass Fe and Mn in the finer textured upland topsoil vs. the dominantly quartz sand dredge materials. Both Mn and Fe appear to have been mobilized from the A horizons and possibly concentrated in the deeper C horizons. With time, Mn increased in A horizons due to nutrient cycling in litter fall and nutrient retention by accumulating OM, but the Fe content decreased. Over 9 yr (2006–2015), there was a decrease in Mn and Fe in C horizons.

As for microtopography effects, the shallow pits had lower BD, higher TC, and higher TN because they were saturated, if not ponded, most days and collected more OM as litter and floating debris. The convex mounds were elevated higher above daily saturation fluctuations and were more aerated, leading to lower litter retention and net C accumulation. Microtopography may also help retain litter in similar tidally influenced wetlands, 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 growth. The lasting effects with time (from 2003 to 2013) were due to the pit and mound microtopography added to the wetland during construction (Pietrzykowski et al., 2015). Similarly, in this study, there were no lasting compost treatment effects on soil properties (color, BD, OC, or TN) after 12 yr. However, topsoil additions led to more rapid horizon development, stronger structure, and more hydric soil indicators after 12 yr due to the fine texture and original Fe and Mn content of the topsoil amendment.

5 | CONCLUSIONS

For 12 yr following construction and treatment application, soil properties in this created wetland progressed toward natural wetland soil properties: lowered value and chroma in A horizons; strong gleying in the subsoil; development of HSFIs; silt increase in surface soils by sediment trapping; low BD; overall increased mass OC and TN; and an overall average C accumulation rate of 2.0 Mg ha^{-1} yr^{-1} in the top 30 cm. Redox features formed within 2 yr at this site, and HSFIs formed within 4 yr. After the initial formation of redox features, some concentrations reduced by 10.5–16% on average due to the dissolution and leaching of Fe. The wetland uniformly increased in OC and TN in the surface with time, but compost and topsoil treatments did not affect long-term levels.

At the compost rates used (78 and 156 Mg ha^{-1} compost), there seem to be few lasting effects of compost on soil color, BD, OC, or TN after 12 yr in this unique created wetland. In 2015, the mass C to 30 cm was greater in plots that had added topsoil due to the finer texture leading to higher OC retention. Topsoil plots had higher yearly C accumulation in the top 30 cm than plots in Treatment 3. Average soil C-accumulation rates were 0.95 Mg ha^{-1} yr^{-1} in Treatment 3 and 3.03 Mg ha^{-1} yr^{-1} in topsoil Treatment 4. The loamy topsoil soil amendments retained more redoximorphic features after 12 yr than the sandy soil treatments. The addition of fine-textured topsoil to the original sandy soils led to faster soil structure development, more stable HSFIs, and higher BD (although not root limiting).

The addition of microtopography (creation of pits) is a valuable strategy for increasing the variety of local 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 organic amendments to sandy created wetland soils if the initial OM, OC, BD, or hydrology are limiting. However, in this sandy wetland with nearly ideal hydrology (inundated twice per day) and non-limiting BD, compost amendment at these rates had little to no effect on soil morphology and redox features in the long term. Future research is needed to test the long-term impact of adding amendments to other created wetlands with drier and/or less consistent hydrology (e.g., mineral flats) or other soil limitations such as excess compaction.

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CONCLICT OF INTEREST

The authors declare no conflict of interest.

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