Assessment of Soil Quality Parameters of Long-Term Biosolids Amended Urban Soils and Dredge Blends

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

By

Kaitlyn Suzanne Benson

Graduate Program in Environment & Natural Resources

The Ohio State University

2017

Master's Examination Committee:

Professor Nicholas T. Basta, Advisor

Associate Director and Associate Professor Brian K. Slater

Assistant Professor G. Matthew Davies

Abstract

Soil quality has been defined by Doran and Parkin (1996) as the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health. A multitude of physical, chemical, and biological parameters can be assessed to provide a comprehensive picture of soil quality. The overall objective of this study was to evaluate long term soil restoration and development of manufactured soil dredge blends by using these soil quality parameters. Chapter 1 assessed the soil quality of an urban site treated with biosolids or compost by comparing data collected over years of sampling after one initial application of the treatments. The results show that biosolids-based treatments leads to overall greater long-term soil quality than compost treatments. However, soil phosphorus in the biosolids-treated soils were of concern for runoff and surface water quality harm. Therefore, the study concludes that no treatment was the ideal amendment for overall improved soil quality, and that a blend of compost and biosolids together could be of interest in future research. In Chapter 2, soil quality parameters were used to assess dredge as a main ingredient in manufactured soil blends. With Ohio regulation changing how dredge must be disposed of, research into the beneficial reuse of soil-like dredge material is vital. Blends were designed by incorporating dredge materials, composts and clay then followed by a bioassay growing rye grass. Interestingly, the smaller size fraction dredge material, which is believed to be unsuitable for reuse, resulted in greater soil quality for the majority of the parameters. The addition of a compost material improved the blends, while clay and fertilizer additions did not result in greater soil quality or plant yield. Dredge showed to be a suitable material in manufactured soil blends for beneficial reuse.

This thesis is presented as a series of manuscripts intended for publication in the Journal of Environmental Quality, a publication of the American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America. Additional formatting changes are made to follow The Ohio State University's thesis guidelines.

Acknowledgments

My sincerest thanks to my Academic Advisor Dr. Nicholas T. Basta, who has challenged and supported me to become a better scientist, teacher, and young professional. I also want to thank many of my peers and friends who have helped me during this journey: Matthew Bright, Dr. John Obrycki, Peter McDonough, Dr. Brooke Stevens, Alyssa Zearley, Dave Tomashefski, Nall Moonilall, and Chloe Turner. My friends and family have always been there to pick me up to keep me going through the challenging years to reach my academic goals and I want to thank them for the constant support. Lastly, I need to extend my thanks to Dr. Patrick Drohan of the Pennsylvania State University. Through his teaching and mentorship, I found a love and passion for soil science that shaped my future in a way I am so grateful for.

Vita

2011..Elizabethtown Area High School

2015..B.S. Environmental Resource Management,
The Pennsylvania State University

2017..M.S. Environment and Natural Resources,
Soil Science Specialization,
The Ohio State University

Fields of Study

Major Field: Environment and Natural Resources

Table of Contents

List of Tables

List of Figures

Chapter 1:

Assessment of Long-Term Soil Quality Parameters of an Urban Soil Treated with Biosolids and Compost Amendments

ABSTRACT

Urban soils can show signs of degradation such as a decline in soil structure, compaction, reduced infiltration, less organic matter, salt imbalance, changes to pH levels, and a less diverse soil microbial community (Lal & Stewart, 1992). Experimental plots were established in 2009 on urban soils in Calumet, IL where biosolids and compost treatments were applied to assess and compare effects on soil quality. Treatments were incorporated into the top 12.5 cm of the soil and were: biosolids at 202 Mg ha^{-1} , biosolids at 404 Mg ha^{-1}, compost at 137 Mg ha^{-1}, and a blend of biosolids, drinking water treatment residuals, and biochar. After initial application and seeding, plots were left undisturbed and were sampled multiple times over a 7 yr span. Contradictory to current Illinois Environmental Protection Agency (ILEPA) soil amendment recommendations (Basta et al., 2015), biosolids outperformed compost for multiple soil quality parameters including soil N, total and organic soil C, plant available macro and micronutrients, cation exchange capacity, and soil pH. The greater biosolids application, however, led to excess soil P which could lead to runoff causing surface water and environmental harm. With all of this considering, the study concluded that none of the treatments were perfect or led to better soil quality for all parameters. Future research could develop treatments that incorporate both biosolids and compost together, to assess if a blended treatment could utilize the benefits of both materials at improving urban soil quality.

INTRODUCTION

Interest in the use of biosolids as a soil amendment has grown over the past three decades. Land application of biosolids is seen as a sustainable reuse of a waste product as a beneficial source of organic matter and nutrients for soils. Biosolids are of interest in the Calumet River area, southeast of Chicago, IL. This area is a historical site of heavy industry, landfills, and railroads, where soil disturbance is prevalent. The Metropolitan Water Reclamation District of Greater Chicago (MWRD) has previously used biosolids in ecological restoration projects in the area. However, the use of biosolids as a suitable restoration material has been questioned by the US Fish and Wildlife Service and subsequently led the Illinois EPA to change the specifications for soil amendments from biosolids to a 5.08-cm (2-inch) layer of leaf compost (Basta et al., 2015).

To assess the ability of biosolids versus compost at improving urban soil quality, twenty experimental plots were installed in 2009 and treated with four biosolids and compost based amendments. Sampling has occurred multiple times over the past seven years to properly assess temporal effects on amendments and soil quality.

Objectives

1. Evaluate soil quality parameters of experimental plots including biological, chemical and physical properties.
2. Assess and compare the long-term success and improvements made to soil quality by different biosolids and compost treatments.

MATERIALS AND METHODS

Twenty experimental plots were established in 2009 on a research site of approximately 0.1 ha on the property of Metropolitan Water Reclamation District of Greater Chicago's (MWRD's) East Calumet wastewater treatment and biosolids processing facility, 330 East 130th St, Chicago, IL. (Fig. 1). The plots were 9.14 m x 2.13 m in size, bordered with fabricated steel liners and were spaced 0.46 m apart. To simulate degraded soil conditions, the top 15.2 cm of soil and vegetation was removed mechanically (Basta et al., 2015). The experiment had a completely randomized design (n=4) and each plot was treated with one of the following treatments in 2009 (Table 1): (1) biosolids at 1 in application rate (BS1), (2) biosolids at 2 in application rate (BS2), (3) leaf vegetative compost, (4) Blend of biosolids, drinking water treatment residuals, and biochar, and (5) Control. The biosolids were from the biosolids processing facility located on site and the compost was a certified municipal waste of the Composting Council, Chicago, IL. Each treatment was rototilled in to a depth of 4 in. Plot instillation and treatment application was completed in the fall of 2009, followed by the plots being seeded by hand broadcast with a restoration mix of grass and forb seeds in the spring of 2010, and then again in fall 2010 (Basta et al., 2015). Cellulose seed germination mats were then rolled on top of plots to protect the seeds and improve germination. No additional tillage, fertilizer or treatments were applied to the plots.

Soil sampling was conducted in 2009, 2010, and 2011 and is reported in Basta et al. (2015). In the current study, soil sampling was conducted in 2016 after 5 years of no site disturbance to evaluate long term effects of soil amendments. Ten soil subsamples were collected to make one soil composite sample per plot. The composite samples were air-dried, thoroughly mixed, and passed through a 2 mm sieve. Core sampling was used for bulk density analysis. Two 2 in x 4 in cores were taken per plot; one on the north end, and one on the south end. In-field sampling to determine hydraulic conductivity using Mini Disk Infiltrometers followed the same scheme as the core sampling.

Texture Analysis

A particle-size analysis was completed using the pipette technique (Gee & Bauder, 1986). This is a measurement of the size distribution of individual particles in a soil sample which disperses aggregates into soil particles of sand, silt and clay (Gee & Bauder, 1986). The method concludes by giving a sand and clay percentage of each sample which is used to determine soil texture using the textural triangle for the USDA classification scheme.

Biological Soil Quality Measurements

Potentially Mineralizable Nitrogen

The Soil Protein Index can be used as an indicator of the organically bound nitrogen in soil organic matter. The nitrogen fraction can be made plant available for plant uptake through microbial-assisted mineralization, and is often referred to as Potentially Mineralizable Nitrogen (PMN) (Gugino et al., 2009). The samples were analyzed using the Autoclaved Citrate Extractable Protein Index method (Gugino et al., 2009; Wright &

Upadhyaya, 1996). Samples were processed for the method using the Pierce BCA Protein Assay Kit as recommended by the Cornell Soil Health Lab (Smith et al., 1985). After analysis, the absorbance of each sample was plotted against standard solutions with known protein contents. Protein content is then calculated and shown in mg of Protein per g soil.

Total Carbon and Nitrogen

Total C and N was determined in soil (< 250 μm) and analyzed using a Carlo Erba Elemental Analyzer 1108. The technique used for the determination of C and N is based on the quantitative "dynamic flush combustion" method (Nelson & Sommers, 1996; Bremner, 1996).

Active Carbon

Biologically active soil C was determined using the method described in the *Comprehensive Assessment of Soil Health Cornell Framework Manual Third Edition* (Gugino et al., 2009). Potassium permanganate ($KMnO_4$) solution is used to oxidize active C followed by colorimetric analysis (Gugino et al., 2009; Weil et al., 2003). Absorbance was measured at 562 nm on a spectrophotometer. Active C was expressed as mg C per kg of soil.

Total Organic Carbon

The method used for total organic C was a microwave assisted digestion of the soil (0.5 g < 250 um) using potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid (Heanes, 1984; Nelson & Sommers, 1996). The microwave unit used for analysis was the CEM Mars Unit programmed to 135°C for 30 minutes (Heanes, 1984). In this method, organic C oxidized is equivalent to the Cr (VI) reduced to Cr (III). The amount of Cr (III) produced is measured colorimetrically using a spectrophotometer at 600 nm. Soil mass was reduced to 0.25 g for extremely high levels of organic C being present in samples.

Macronutrients and Micronutrients

Plant available P, K, and micronutrients were determined by soil extraction using Mehlich 3 (Mehlich, 1985). In this method 1 g soil (< 2 mm) was extracted with 10 mL of Mehlich 3 solution for 5 min. Extracted P, K, and micronutrients were analyzed by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP).

Soil Respiration

Metabolic activity of the soil microbial community can be expressed as soil respiration, which is measured by capturing and quantifying carbon dioxide (CO_2) expired from a soil (Gugino et al., 2009). The method used is described in the *Comprehensive Assessment of Soil Health Cornell Framework Manual Third Edition* (Gugino et al., 2009). The method involves rewetting air dried soil, incubating in an airtight container for 4 days and measuring the respired CO_2 (Franzluebbers et al., 1995; Zibilske, 1994). The CO_2 is captured in a trapping solution of KOH within the airtight container and the electrical conductivity of the trap is recorded after incubation (Wollum & Gomez, 1970; Wolf et al., 1952). Respired CO_2 is calculated by comparison of the conductivities of the original KOH solution and a solution representing CO_2 saturation of K_2CO_3 (Gugino et al., 2009).

Plant Biomass

Destructive, direct sampling technique was used to measure above ground plant biomass. One square meter frames assembled from PVC piping were placed randomly in each plot. The vegetation within the frames was clipped within 2-4 cm of the soil surface. Clipped vegetation was then collected in large paper bags and transported for analysis. The samples were then oven dried at 50°C for 48 hours. Total plant biomass by dry weight was then recorded in g per square meter for each plot.

Chemical Soil Quality Measurements

Cation Exchange Capacity

The method to find soil cation exchange capacity (CEC) is described by Sumner & Miller (1996). Soil (1 g, <2 mm) was extracted with 0.1 M $BaCl_2$ with subsequent analysis of exchangeable cations (Ca, Mg, Na, K, Al, and Mn) by ICP. The CEC was then calculated from sum of the exchangeable cations.

Soil pH and Salinity

Soil pH was determined in 1:1 soil:water solution using a glass electrode (Thomas, 1996). Soil salinity was determined by measuring electrical conductivity (EC) (Rhodes et al., 1996).

Elemental Analysis

Inorganic metal contaminants were analyzed in soil (< 250um) using X-ray fluorescence with an XRF Niton XL2 analyzer as described in USEPA Method 6200 (EPA, 2007).

Physical Soil Quality Measurements

Available Water Capacity

The amount of water that a soil can hold that is available for plant uptake is referred to as available water capacity (AWC). It is calculated by

$$AWC = FC - PWP \qquad \text{(Cassel \& Nielsen 1986)}$$

Field capacity (FC) is the upper end of soil wetness after water has drained from gravity, and permanent wilting point (PWP) is the lower end when only water unavailable to plants is left (Gugino et al., 2009). Container capacity (CC) method was used for this study to substitute for FC (Cassel & Nielsen 1986) which assesses the water holding capacity of a soil medium within a pot instead of an in-field measure. PWP was found using a pressure plate extractor (Dane & Hopmans, 2012) when soil is placed on ceramic plates inserted into high pressure chambers. Water is extracted from soil until 1500 kPa is reached. PWP results were then subtracted from CC results to give AWC expressed as g of water per g of soil.

Bulk Density

The core method was used to find bulk density as descried by Blake & Hartage (1986). Two 2 x 4 in cores were taken for each plot; one on the north end and one on the south end of each plot. Each core was oven dried at 105°C and bulk density was then calculated by dividing the mass of oven dried soil by the volume of the core (Blake & Hartage, 1986). Mean bulk density of the two cores was determined for each plot.

Aggregate Stability

Wet aggregate stability was found using a Cornell Sprinkle Infiltrometer that releases raindrops of 4mm diameter and delivers a simulated rain event to the soil of 15 drops per second, equivalent to a heavy thunderstorm (Gugino et al., 2009). The method is described in the *Comprehensive Assessment of Soil Health Cornell Framework Manual Third Edition* (Gugino et al., 2009) which is compiled from methodology of Ogden et al. (1997) and van Es et al. (2006).

Hydraulic Conductivity

Mini-Disk portable tension infiltrometers were used in-field to measure unsaturated hydraulic conductivity. Methodology for the Mini-Disk infiltrometers is outlined in the manual *Mini Disk Infiltrometer* (Decagon Devices Inc., 2014). The infiltrometers were placed in 2 randomly selected points in each plot; one on the north end and one on the south end of each plot. The vegetation was cut down at each point and the infiltrometers were placed directly on a level section of the bare soil surface. The suction rate was set to 0.5-1 cm/s. Every 30 sec the amount of infiltrated water was recorded on a data sheet. This was recorded for 10 minutes, or until the infiltrometer was emptied of water. Hydraulic conductivity was then calculated using a worksheet supplied by Decagon Devices using Zhang (1997) methodology to plot cumulative infiltration versus square root of time and factoring in soil type and suction rate of the device (Decagon Devices Inc., 2014).

Statistical Analysis

The experimental design had five treatments with four replicates. Data was statistically analyzed using Minitab Version 17 (Released 2016) for Windows. One-way analysis of variance (ANOVA) was conducted and multiple means comparisons were conducted by Tukey honestly significant difference (HSD). The level of significance for all statistical comparisons was α=0.05.

RESULTS AND DISCUSSION

Biological Soil Quality Measurements

Nitrogen

Total soil N was BS2 > blend, BS1 > compost, control (Fig. 2; Table 3). Biosolids and blend treatments have significantly higher total N compared to the control but compost did not increase soil N. Total N results are consistent with the N content applied to plots in 2009; BS2 (6.34 Mg ha^{-1}) > Blend (3.21 Mg ha^{-1}) > BS1 (3.17 Mg ha^{-1}) > Compost (1.38 Mg ha^{-1}) > Control (1.62 g kg^{-1} background total N) (Table1; Table 2). The increased total N in biosolids treated soils persisted over the 7 years (Fig. 3). Potentially mineralizable nitrogen (PMN) was BS2 > blend, compost ≥ BS1 ≥ control (Fig. 4; Table 3). The addition of the N-rich biosolids facilitated N mineralization and increased both total N and PMN with the greater biosolids application rate. This trend of increased N with biosolids application persisting long term has also been reported in White et al. (1997). Likewise, Brown et al. (2014) also supports that biosolids-treated soils have greater soil N compared to compost-treated soils long term.

Carbon

Total Carbon showed that BS2 ≥ blend ≥ BS1 ≥ compost ≥ control. BS1, BS2, and blend treatments were all significantly larger than the control soil, while compost did not show a significant increase (Fig. 5; Table 3). These results are consistent with the amount of total C added to the plots in 2009; BS2 (81.2 Mg ha^{-1}) > Blend (46.0 Mg ha^{-1}) > BS1 (40.6 Mg ha^{-1}) > Compost (22.1 Mg ha^{-1}) (Table1; Table 2). Li & Evanylo (2012) supports this trend of increased soil C with increased biosolids application persisting years after application. Brown et al. (2014) also shows that biosolids-treated soils have greater soil C compared to compost-treated soils over time. Active carbon trended to be larger in all treatments (552 to 617 mg C /kg) compared to the control (525 mg C/kg), however the increase was not significant at $P < 0.05$ (Fig. 6, Table 3). Similar to total carbon, BS2 has the largest total organic carbon (TOC) content and compost does not show a significant increase from the control (Fig. 7). Organic carbon was BS2 ≥ blend ≥ BS1 ≥ compost, control which is consistent with TOC inputs added to plots in 2009 (comparable to total C inputs) (Table 2). Li & Evanylo (2012) reported that surface soil TOC steadily decreased per year after biosolids application as the organic matter stabilized. Data from 2009-2011 support this, however 2016 data does indicate a spike in soil TOC (Fig. 8) which could be due to an increase in biomass in plots.

C:N Ratio

Total C:N trend was BS2 ≤ BS1, blend ≤ compost < control (Fig. 9; Table 3). The C:N was inversely related to the N added per plot (BS > compost > control) (Table 2). The control soil showed a significantly higher C:N ratio compared to all treatments, with BS2 as the lowest C:N ratio. BS1 and BS2 treatments show a steady increase in C:N ratio over the 7 year span (Fig. 10), after an initially low C:N ratio due to the N-rich biosolids application. After application of N rich biosolids, C:N ratios increase approaching the control soil C:N ratio of 23:1 (Table 2). Over time the increase in TOC in the biosolids-treated plots led to the C:N ratio to increase and approach soil C:N with stabilized organic residue.

Macronutrients

Plant available P was BS2 > BS1, blend > compost, control. P significantly increased from the control in the BS1, BS2, and blend treatments (Fig. 11; Table 3). The increased level of P is consistent with the P added to plots in 2009; BS2 (7.57 Mg ha^{-1}) > Blend (3.78 Mg ha^{-1}) > BS1 (3.78 Mg ha^{-1}) > Compost (0.38 Mg ha^{-1}) > Control (465 mg kg^{-1} background P) (Table1; Table 2). Treatments corrected potential soil P deficiencies in control soil, however biosolids-based treatments increased P well above the recommended maximum of 200 mg kg^{-1} and can be a threat for surface water runoff and environmental harm (Sharpley et al., 1996). WTR addition in the Blend treatment was intended to reduce P solubility as shown in Elliott et al. (2001) however this effect was not seen (Fig. 11; Table 3). Plant available K did not show significant increase in any of the treatments (Fig. 12; Table 3), however tended to be higher with the greater biosolids applied. Soil K availability persisted after 7 years and all plots had sufficient K for plant growth of 150 mg kg^{-1} (Johnson et al., 2000). Brown et al. (2014) showed that soil macronutrients P and K were generally greater and persisted over long term for biosolids versus compost treatments which supports these results.

Micronutrients

Plant available Cu showed BS2 > BS1, blend > compost, control (Fig. 13; Table 3). A significant increase in plant available Cu is seen in the biosolids-based treatments compared to the control soil (Fig. 13; Table 3). BS2 has significantly larger Cu compared to other treatments, and compost does not show a difference from the control. Soil Cu was sufficient in all amended and control soils. Brown et al. (2014) also found that available Cu persisted over time greater in biosolids than compost. Similarly, plant available Fe significantly increased in biosolids-based treatments while compost did not

(Fig. 14; Table 3). The trend for Fe shows BS1, BS2, blend > compost, control. Acidic soils can lead to higher available Fe, and this trend is seen as the site soil has the highest pH (7.39) (Table 2) with the lowest available Fe levels (110 mg kg^{-1}) (Table 3). Biosolids addition lowered soil pH (Fig. 20) and similarly increased available Fe (Fig. 14; Table 3). Plant available Zn follows the same trend as plant available Cu which is BS2 > BS1, blend > compost, control (Fig. 15; Table 3). Zinc availability does not increase in the compost, but does in biosolids-based treatments. Biosolids are high in total Zn, therefore the increase in available Zn (Fig.15) was expected. In general, biosolids increased the plant available pool of micronutrients which was also seen by Brown et al. (2014).

Respiration

Soil respiration tends to be greater in BS2 (2.01 mg CO_2 g^{-1}), however no treatment is significantly higher than the control (1.58 mg CO_2 g^{-1}) (Fig. 16; Table 3). The greater soil respiration was expected with the biosolids based treatments due to greater C for microorganism consumption. Carlson et al. (2015) assessed the biological properties of these plots 3 years after application. Biosolids showed greater microbial activity one year after application, after which generally showed a steady decline. This is thought to be due to a reduction of components for microbes that are readily available during early stages of decomposition (Carlson et al., 2015). Results in 2016 generally agree with this idea. Although soil respiration and microbial activity declines, values are still well within a range for a healthy soil (Gugino et al., 2009).

Plant Biomass

Treatments BS1, compost and blend show a significant increase in plant biomass (Fig. 17; Table 3). The trend was blend, compost, BS1 ≥ BS2 ≥ control. Vegetation within the control and compost treated plots appeared lethargic and slightly yellowing (Fig. 18). The increase in plant biomass production is due to the increase in plant-available N from amendment additions. The blend treatment had the second largest amount of N applied to the plots which led to the largest plant growth and vegetative cover (Table 2). It was expected that BS2 would have the highest response for plant growth because it was the largest N application, however this was not seen. The results show that vegetative growth response was best with lower biosolids application (Fig. 17; Table 3). The forbes and grass species growth response trend is similar to the results of Pierce et al. (1998). Perennial grass growth has a curvilinear response to biosolids application (Pierce et al., 1998), meaning that biosolids addition does increase plant yield but starts to decrease at a point. This can explain why BS2 did not show the highest plant biomass growth as expected.

Chemical Soil Quality Measurements

Cation Exchange Capacity

Soil CEC trend was BS2 > blend, BS1 > compost, control (Fig. 19; Table 3). The biosolids-based treatments showed a significant increase in CEC, while the compost treatment did not differ from control. The same trend was also identified by White et al. (1997), that with greater biosolids application, soluble cations were more prevalent and persisted years after application. Clay and organic matter increase in a soil leads to a greater soil CEC, however the biosolids-based treatments did not have greater clay than the compost or control soils (Table 4). Therefore, the increase in organic matter in the biosolids is leading to the increase in soil CEC for the biosolids-treated soils.

Soil pH and Salinity

All treatments show a significant decrease in soil pH compared to the control (Fig. 20; Table 3). The trend shows BS2 < BS1, compost, blend < control. The decrease in soil pH is consistent with the lower pH of amendments added to the plots (Table 2). It was expected that biosolids would decrease soil pH due to the low C:N ratio leading to N mineralization. As the soil N converts from organic N to NH_4^+, the soil pH lowers which is seen even 7 years after initial application. The BS2 treatment decreased the soil pH enough to fall within the optimum soil pH range for plant growth between 6.5-7.0 (Table 3). This trend of decreased pH with increased biosolids application was also seen in White et al. (1997). Soil salinity was BS2 ≤ blend, control, compost ≤ BS1 (Fig. 21; Table 3). Soil salinity does not vary significantly from the control (1.14 dS m^{-1}) in any treatment, however BS2 treatment (0.33 dS m^{-1}) tends to be lower and is significantly lower than BS1 (1.40 dS m^{-1}) (Fig. 21; Table 3). White et al. (1997) reported that initial soil salinity was significantly higher with larger biosolids application and noted that over time soil salinity decreased in those soils which is also seen in these results.

Heavy Metals

Total zinc and copper trends were the same: BS2 > blend, BS1 > compost, control. Total Zn and Cu concentrations increased in biosolids-based treatments compared to the control and did not significantly increase in compost (Figures 22, 23; Table 3). The increase in total Cu and Zn is expected as elevated levels are often seen in biosolids. Long-term elevated levels of Cu and Zn in biosolids treated soils has previously been reported (White et al., 1997). Total Cu and Zn in all plots do not exceed Illinois state soil concentration standards of 2,900 mg Cu kg^{-1} or 23,000 mg Zn kg^{-1} (ILEPA, 2013). Total Pb concentration significantly increased only in the BS2 treatment (Fig. 24; Table 3). White et al (1997) also saw this trend that the greater the biosolids application, the greater Pb concentration in topsoil over time. However, the plots soil Pb is below level of concern according to federal and Illinois state soil concentration standards of 400 mg Pb kg^{-1} ILEPA (2013). In general, neither compost nor biosolids applications lead to elevated heavy metal concentrations.

Physical Soil Quality Measurements

Available Water Capacity

Treatments did not significantly differ from the control for AWC, however BS1 and BS2 (0.58 g g^{-1}; 0.45 g g^{-1}) tended to show higher AWC compared to compost (0.25 g g^{-1}) (Fig. 25; Table 3). These results were unexpected because Brown et al. (2014) showed biosolids-treated soils have higher water holding capacity compared to compost-treated soils years after application. However, the control soils of this study are adequate for AWC (>0.2 g g^{-1}) (Gugino et al., 2009) so a significant improvement was not achieved.

Bulk Density

Bulk density did not significantly vary in any of the treatments (Fig. 26; Table 3), however BS1 and Blend treated-soils did tend to have slightly lower bulk densities. It was expected that the biosolids-based treatments would lead to lower bulk densities, comparable to an organic soil. Brown et al. (2014) showed that bulk density did not significantly decrease with compost addition but did tend to decrease with larger biosolids application. The results from this study do vary from Brown et al. (2014), however show a similar trend. Similar to AWC, the control soil does have an adequate bulk density of <1.6 g cm^{-3} (Brady & Weil, 1996), so a significant improvement was not seen.

Aggregate Stability

Aggregate stability was BS2 ≤ BS1, compost, blend ≤ control (Fig. 27; Table 3). Aggregate stability did not significantly vary from the control in BS1, compost, or the blend however BS2 did show a significant decrease in percent stable aggregates (Fig. 27; Table 3). These results do not follow those of Tsadilas et al. (2005), who found that aggregate stability increases with biosolids addition when reapplication occurs. Similar to bulk density results, these contrasting findings could be due to the lack of re-application of biosolids treatment in this study. Biosolids will increase aggregate stability if reapplication occurs (Tsadilas et al., 2005), however in the long-term this may not hold true when reapplication ceases. As well, all soils did show greater than adequate aggregate stability of >40% (Gugino et al., 2009) so an improvement was not achieved.

Hydraulic Conductivity

Hydraulic conductivity results were variable between and within plots, and do not show a consistent pattern (Table 4). Of the 40 hydraulic conductivity readings conducted, only 11 fall within the Moderate K_{sat} class (4.23-14.11 µm s^{-1}) which is standard of the soil textures of the plots according to the USDA NRCS for Silt Loam and Loam textured soils. The majority (23 readings) fell within the Moderately Rapid K_{sat} class (14.11-42.34 µm s^{-1}) (Table 4). Lastly, 6 samples even classified as Rapid K_{sat} class (42.34-141.14 µm s^{-1}) typical of sand/loamy sand soils, all of which were biosolids-based treated soils (Table 4). It appears that many of the plot soils are showing water infiltration traits of much sandier soils. This can be due to the increase in organic matter from biosolids addition. These results are similar to those of Tsadilas et al. (2005) that showed an increase in biosolids application leads to higher water infiltration rate.

CONCLUSIONS

In general, biosolids-based treatments lead to greater soil quality for multiple parameters over the long-term. After 7 years since application, the soils treated with biosolids tended to have greater soil N, total and organic soil C, plant available macro and micronutrients, cation exchange capacity, and a lower pH for improved plant growth.

Physical properties did not significantly improve, however control soil plots had already adequate physical properties so an improvement was not seen. A drawback for biosolids land application is potential for phosphorus runoff, and it was found that even years after application, biosolids-treated soils still have plant available P levels of concern. This was anticipated by assessing the addition of water treatment residual for reducing P solubility, however an improvement was not significantly seen. Currently the soil amendment recommended by the ILEPA is compost, however these results show that soil treated with compost does not lead to greater soil health over time compared to soils treated with biosolids. The reuse of biosolids as a topsoil amendment can lead to better soil quality for degraded urban soils than compost. With these considerations, this study showed that none of the treatments were perfect. Biosolids led to many soil quality improvements, however compost led to much better soil P levels. Therefore, future research could potentially develop treatments that incorporate both biosolids and compost blended together, which may lead to a better urban soil treatment for improved soil quality in all facets.

Table 1. Treatment descriptions and application rates

Abbreviation	Treatment	Application Rate	Plots
BS1	Biosolids	202 Mg ha^{-1} (2.5 cm layer)	3, 8, 11, 13
BS2	Biosolids	404 Mg ha^{-1} (5.1 cm layer)	6, 7, 10, 12
Compost	USCC certified hardwood vegetative compost	137 Mg ha^{-1} (2.5 cm layer)	9, 17, 18, 20
Blend	Blend of:		1, 14, 15, 19
	• MWRD biosolids	202 Mg ha^{-1}	
	• Drinking water treatment residual (WTR)	10.3 Mg ha^{-1}	
	• Biochar	5.7 Mg ha^{-1}	
Control	none		2, 4, 5, 16

Table 2. Selected properties for site soil, amendments, and components of amendments.

Material	**pH**	**P_{ox}**	**Al_{ox}**	**Fe_{ox}**	**PSI**	**Total P**	**Total C**	**TOC**	**Total N**
		—	$g\ kg^{-1}$	—		$mg\ kg^{-1}$	—	$g\ kg^{-1}$	—
Site Soil	7.39	0.21	1.28	5.13	0.05	465	-	37.4	1.62
Biosolids	6.20	19.6	5.70	60.2	1.06	18,730	201	201	15.7
Compost	7.98	1.57	0.48	2.20	0.83	2,797	161	161	10.1
WTR	6.94	0.61	1.03	71.7	0.02	-	97.2	-	4.29
Biochar	7.25	0.10	0.10	0.10	2.66	281	772	-	0.00

Modified from Basta et al., 2016

Table 3. Mean values of key soil chemical, biological, and physical properties of amended and control soils

Parameter	**Soil Treatments**														
	BS1			**BS2**			**Compost**			**Blend**			**Control**		
Biological	mean	sd†		mean	sd		mean	sd		mean	sd		mean	sd	
Total N g kg^{-1}	6.19	0.69	b	8.79	0.78	a	4.34	0.76	c	6.67	0.53	b	3.50	0.53	c
PMN mg g^{-1}	15.5	3.26	bc	22.2	3.17	a	16.1	2.22	b	16.9	1.21	b	10.5	0.66	c
Total C g kg^{-1}	102	12.4	bc	130	9.72	a	79.9	2.84	b	112	13.0	b	76.6	7.68	c
Active C mg kg^{-1}	555	15.5	a	617	48.5	a	587	62.1	a	552	78.2	a	525	72.2	a
TOC g kg^{-1}	83.5	3.91	bc	115	8.10	a	73.3	8.61	c	96.7	11.9	ab	71.4	6.70	c
C:N ratio	16.4	1.33	bc	14.8	0.61	c	18.6	2.38	b	16.8	1.22	bc	22.1	1.78	a
P mg kg^{-1}‡	769	21.4	b	1241	92.3	a	83.5	15.4	c	758	96.5	b	25.4	8.71	c
K mg kg^{-1}‡	257	118	a	380	99.3	a	321	72.3	a	327	107	a	232	21.3	a
Cu mg kg^{-1}‡	26.7	0.57	b	37.3	2.95	a	8.20	0.63	c	26.1	2.14	b	10.2	0.40	c
Fe mg kg^{-1}‡	259	12.8	a	242	17.2	a	145	26.7	b	251	28.3	a	110	4.51	b
Zn mg kg^{-1}‡	98.3	13.7	b	152	8.16	a	24.2	6.03	c	105	12.8	b	18.4	1.44	c
Respiration mg g^{-1}	1.44	0.62	a	2.01	0.38	a	1.40	0.18	a	1.61	0.36	a	1.58	0.32	a
Plant Biomass g m^{-2}	342	22.9	a	300	85.5	ab	355	38.3	a	396	27.5	a	197	60.0	b
Chemical															
CEC $cmol_c$ kg^{-1}	36.0	2.13	b	49.7	3.42	a	29.8	1.60	c	40.7	4.27	b	26.5	2.45	c
Soil pH	7.19	0.08	b	6.98	0.06	c	7.41	0.14	a	7.21	0.05	b	7.45	0.09	a
EC dS m^{-1}	1.40	0.34	a	0.33	0.61	b	1.12	0.57	ab	1.00	0.09	ab	1.14	0.37	ab
Total Zn mg kg^{-1}	441	42.3	b	871	206	a	277	23.0	c	569	70.7	b	162	12.1	c
Total Cu mg kg^{-1}	153	17.2	b	325	79.5	a	55.0	11.8	c	188	20.6	b	46.5	4.12	c
Total Pb mg kg^{-1}	105	11.6	b	141	22.2	a	84.0	9.31	b	103	6.68	b	100	23.3	b
Physical															
AWC g g^{-1}	0.58	0.14	a	0.45	0.19	a	0.25	0.19	a	0.37	0.21	a	0.37	0.24	a
Bulk Density g cm^{-3}	1.29	0.08	a	1.39	0.04	a	1.39	0.05	a	1.24	0.09	a	1.37	0.11	a
Aggregate Stability	71.8	2.27	ab	61.1	8.59	b	72.2	5.17	ab	69.1	9.66	ab	77.1	3.97	a

Means within parameter measured with same letter are not different ($\alpha = 0.05$)

† 1 standard deviation

‡ Mehlich-3 extraction

Table 4. Texture Analysis and Hydraulic Conductivity results for amended and control soils.

Treatment	**Plot**	**Clay**	**Sand**	**Texture Class**	**K_{sat}**	
		—— % ——			—— μm s^{-1} ——	
BS1	3	17.9	28.0	SiL	5.59	11.9
	8	20.3	26.1	SiL	29.0*	39.2*
	11	20.3	30.8	L	25.5*	25.4*
	13	16.4	32.0	SiL	5.89	56.9**
BS2	6	12.6	48.2	L	25.3*	30.1*
	7	14.1	41.6	L	65.5**	61.9**
	10	13.8	27.1	SiL	45.2**	12.2
	12	16.6	33.0	SiL	30.0*	28.8*
Compost	9	22.0	31.7	L	22.4*	7.79
	17	23.3	30.5	L	34.6*	23.4*
	18	19.2	34.2	L	11.5	38.9*
	20	23.3	33.0	L	8.55	8.74
Blend	1	13.3	46.5	L	13.1	44.9**
	14	18.0	34.3	L	43.3**	31.0*
	15	15.2	31.8	SiL	28.1*	40.4*
	19	15.7	30.2	SiL	36.8*	11.0
Control	2	23.1	28.2	L	37.1*	23.0*
	4	26.1	27.6	L	20.3*	17.4*
	5	25.9	27.1	L	10.5	19.2*
	16	26.0	27.4	L	36.2*	23.9*

Values with no indication are within the recommended Moderate K_{sat} class for a Silt Loam / Loam texture class †
*Moderately Rapid K_{sat} class†
**Rapid K_{sat} class†
†According to USDA NRCS Hydraulic Conductivity in Relation to Soil Texture

Fig. 1. Experimental Design. Modified from Basta et al., 2012.

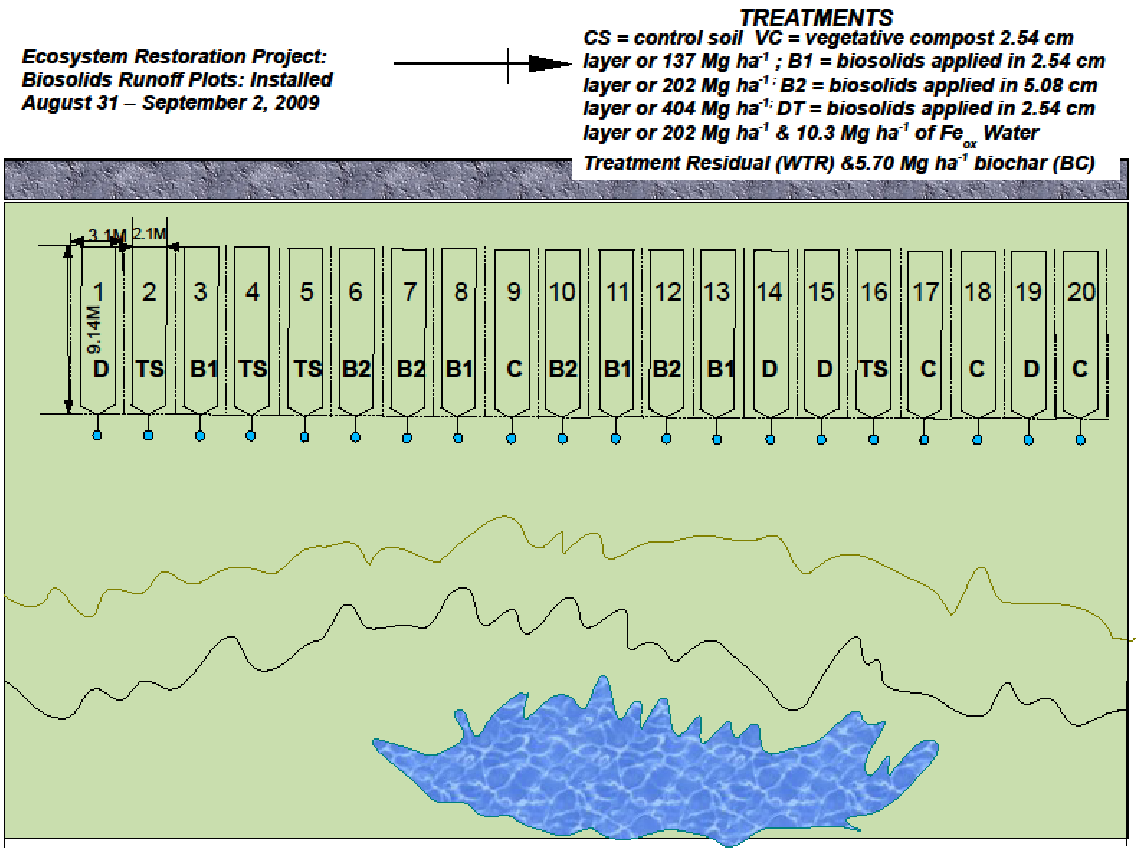


Fig. 2. Comparisons of Total Nitrogen in amended and control soils.

Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD ($\alpha = 0.05$). Soil treatments are BS1 (biosolids at 202 Mg ha^{-1}), BS2 (biosolids at 404 Mg ha^{-1}), Compost, Blend (blend consisting of biosolids applied at 202 Mg ha^{-1}, drinking water treatment residual and biochar), and Control.

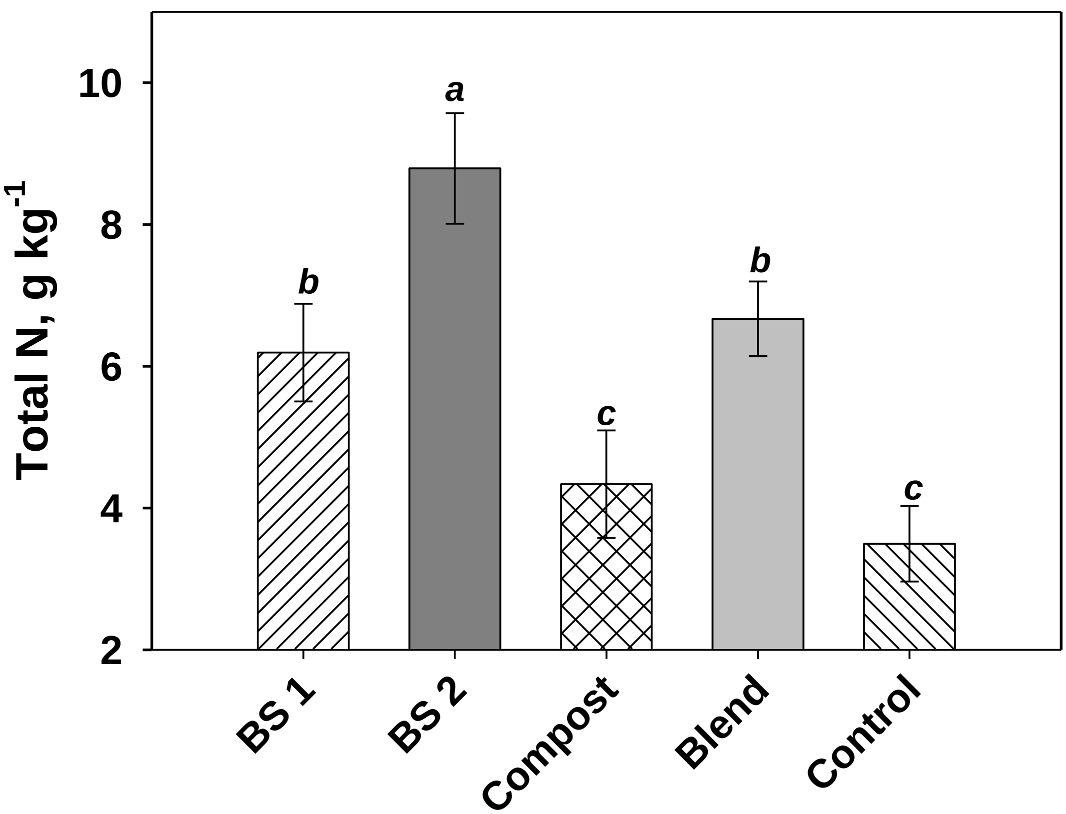


Fig. 3. Change in Total N over a 7 yr span for amended and control soils. Soil treatment abbreviations are defined in Figure 2.

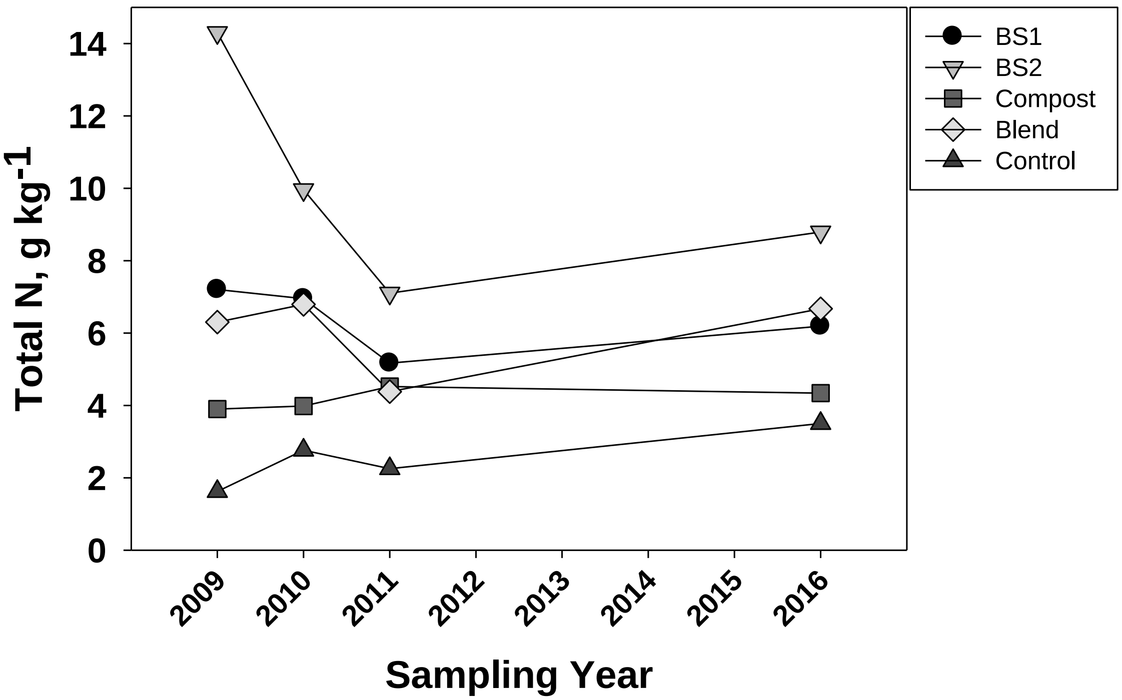


Fig. 4. Comparisons of Potentially Mineralizable Nitrogen (PMN) in amended and control soils. Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD ($\alpha = 0.05$). Soil treatment abbreviations are defined in Figure 2.

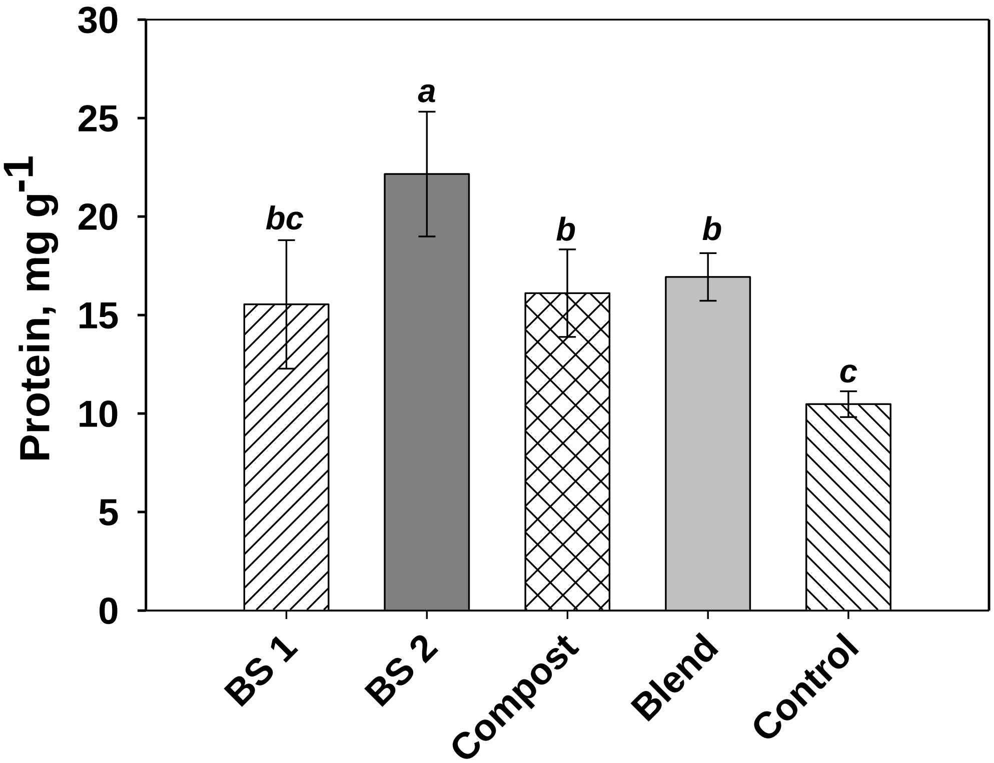


Fig. 5. Comparisons of Total Carbon in amended and control soils.

Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey’s HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

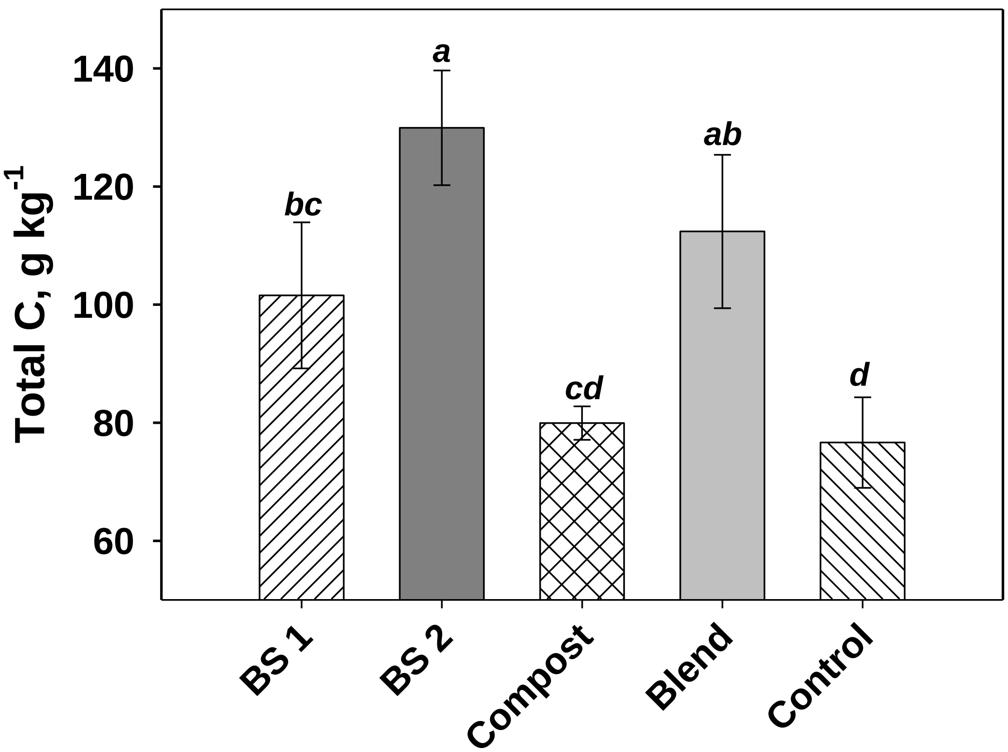


Fig. 6. Comparisons of Active Carbon in amended and control soils.

Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD ($\alpha = 0.05$). Soil treatment abbreviations are defined in Figure 2.

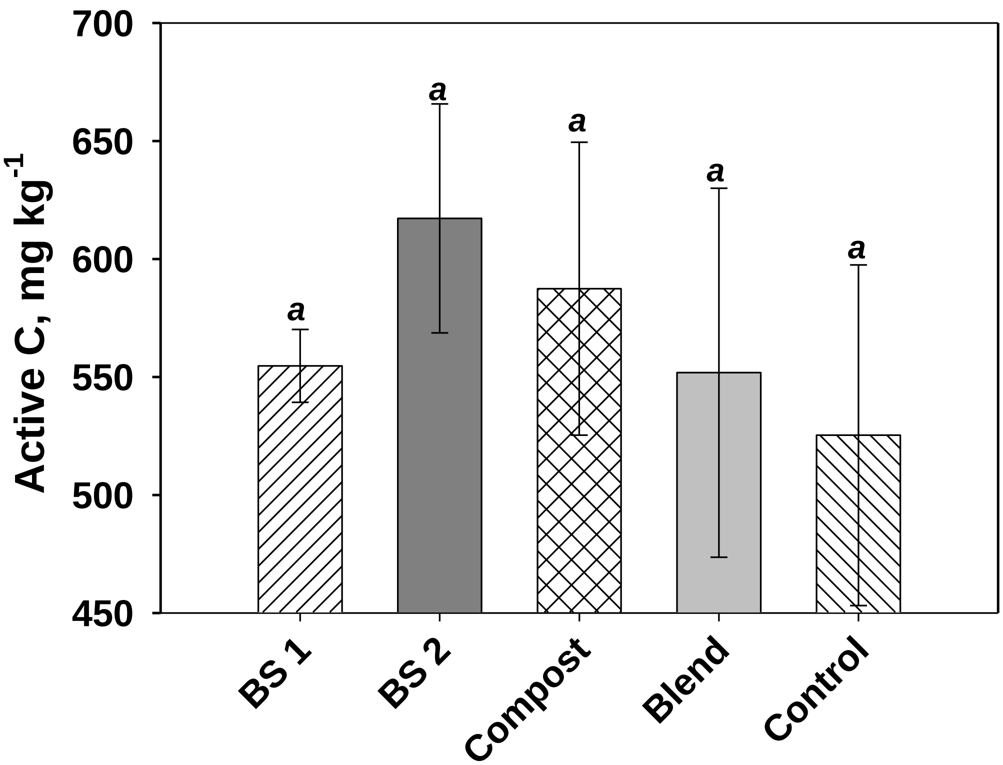


Fig. 7. Comparisons of Organic Carbon in amended and control soils.

Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

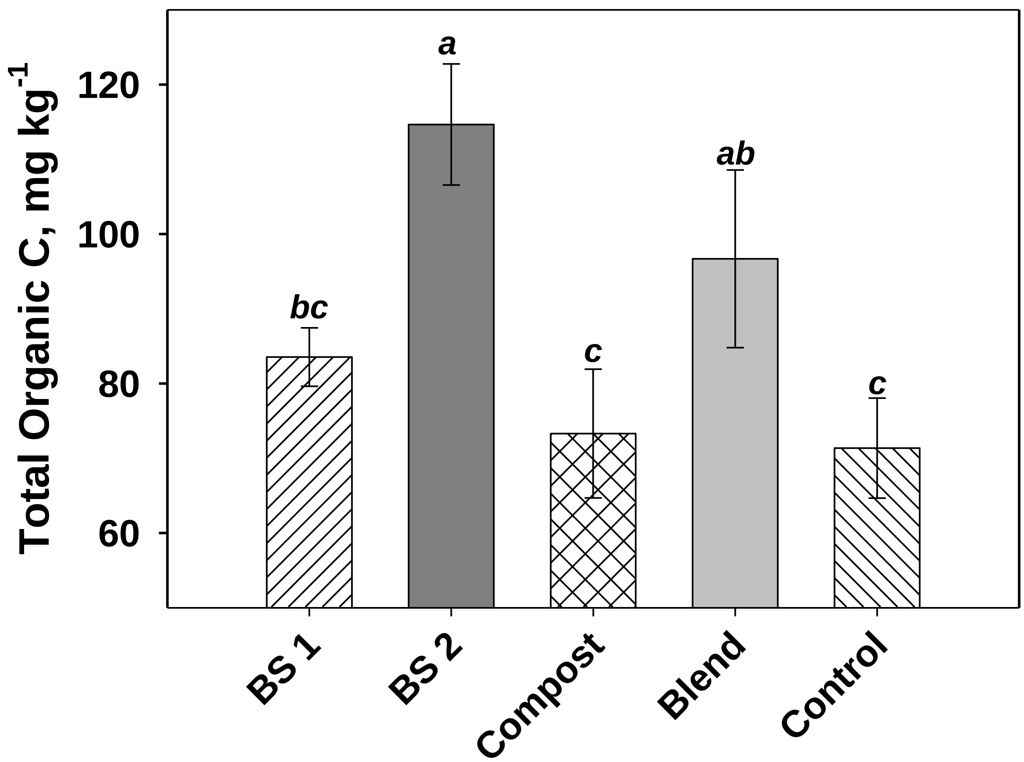


Fig. 8. Change in Total Organic C over a 7 yr span for amended and control soils. Soil treatment abbreviations are defined in Figure 2.

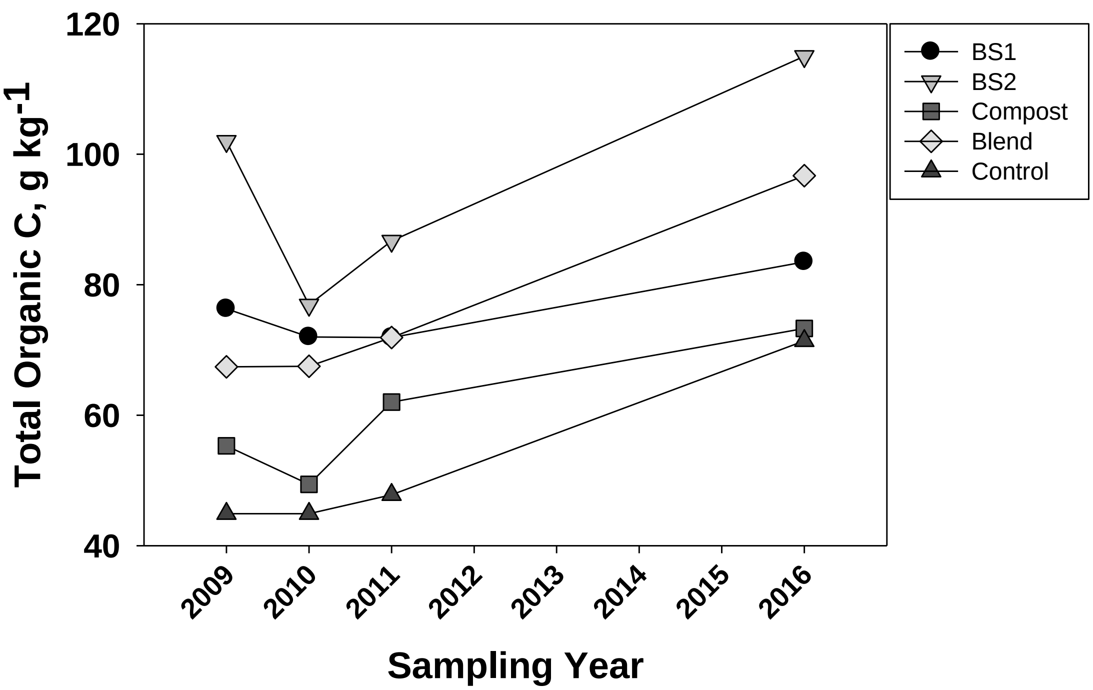


Fig. 9. Comparisons of Total C:N ratio in amended and control soils.

Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

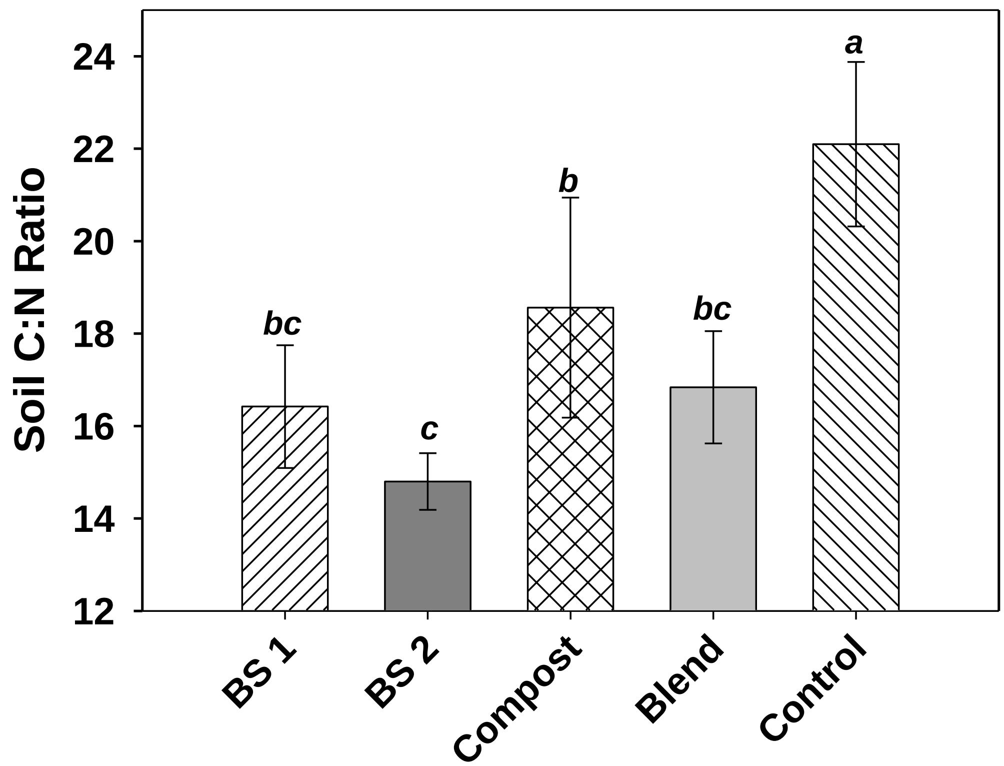


Fig. 10. Change in Soil Total C:N over a 7 yr span for amended and control soils. Soil treatment abbreviations are defined in Figure 2.

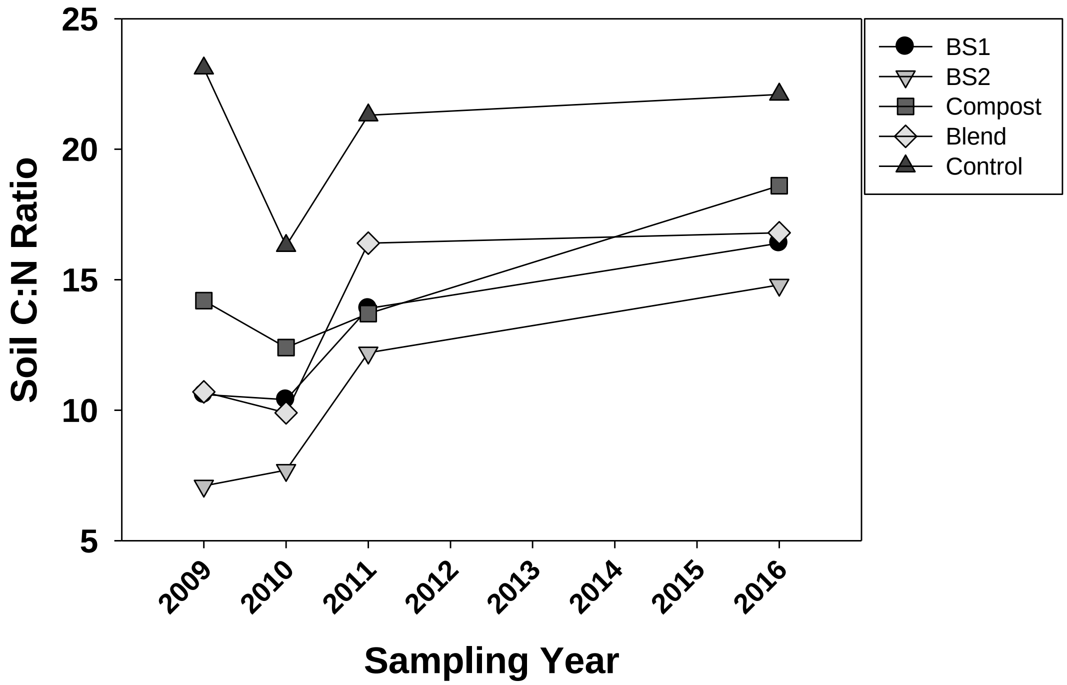


Fig. 11. Comparisons of Plant Available Phosphorus in amended and control soils. Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

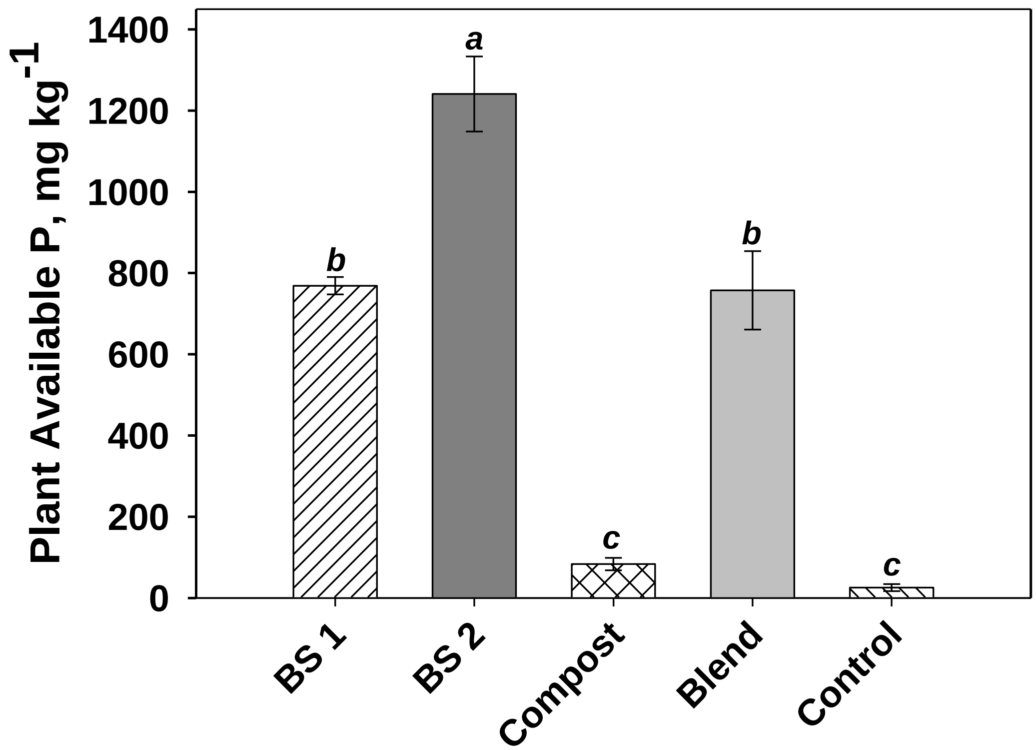


Fig. 12. Comparisons of Plant Available Potassium in amended and control soils. Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD ($\alpha = 0.05$). Soil treatment abbreviations are defined in Figure 2.

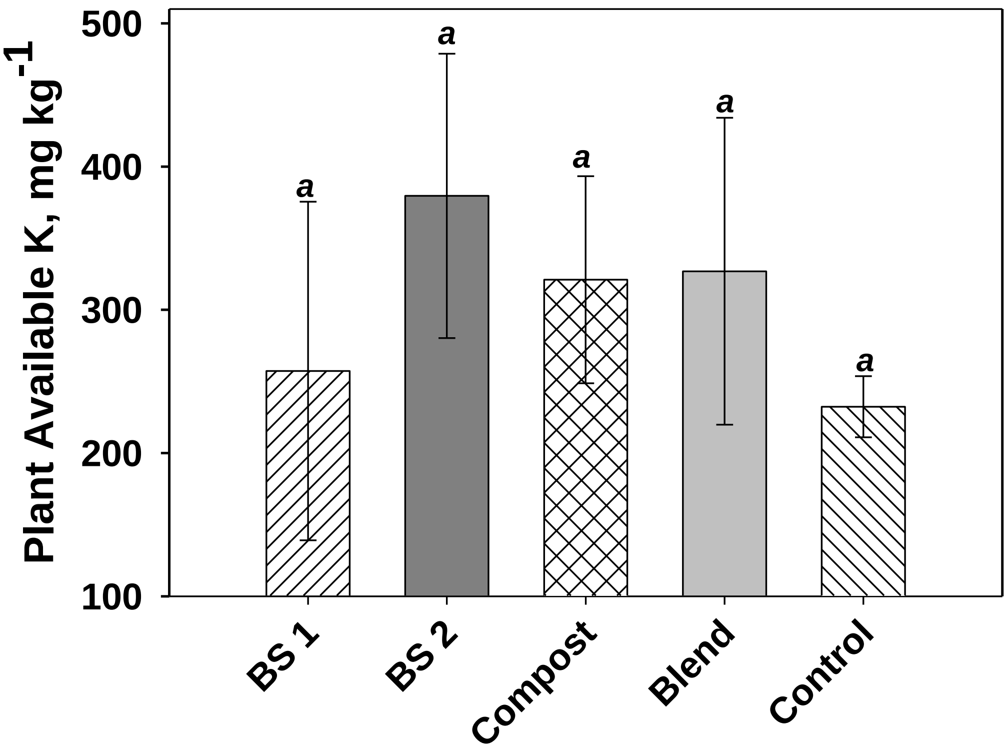


Fig. 13. Comparisons of Plant Available Copper in amended and control soils. Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

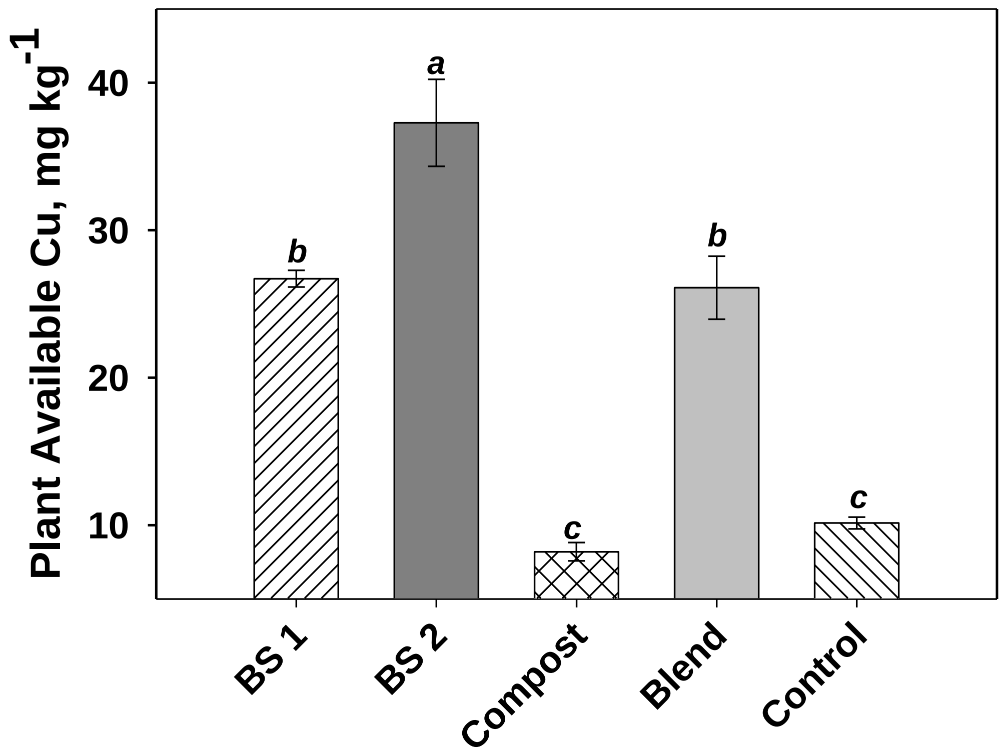


Fig. 14. Comparisons of Plant Available Iron in amended and control soils. Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

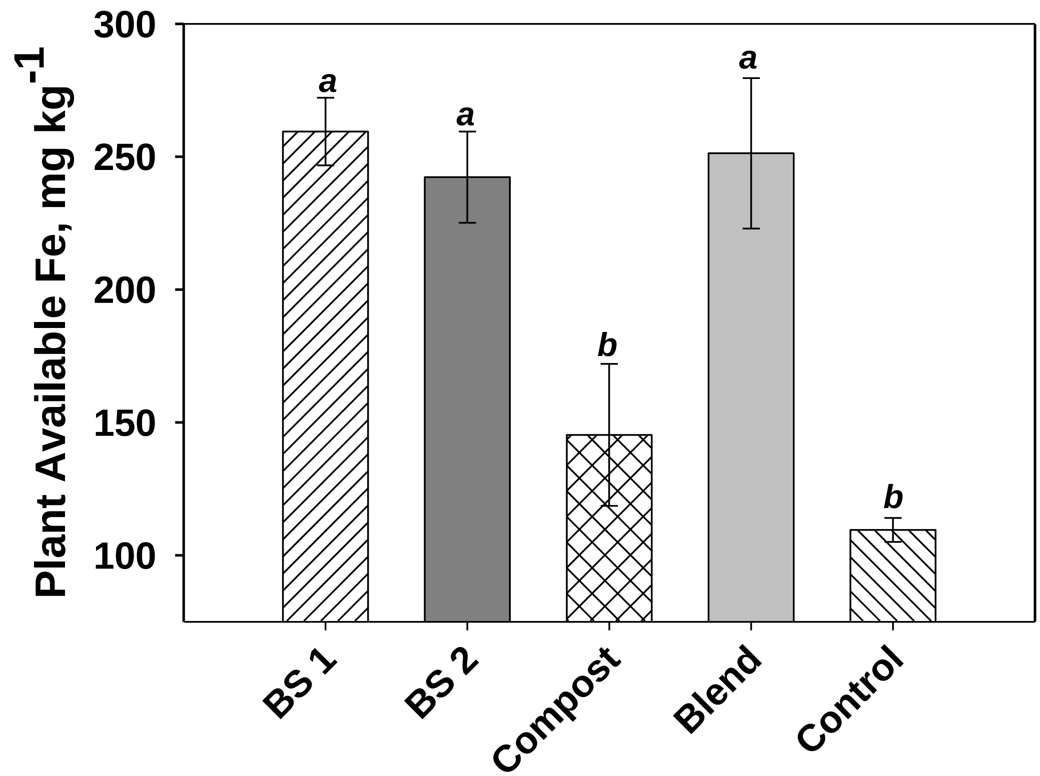


Fig. 15. Comparisons of Plant Available Zinc in amended and control soils. Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

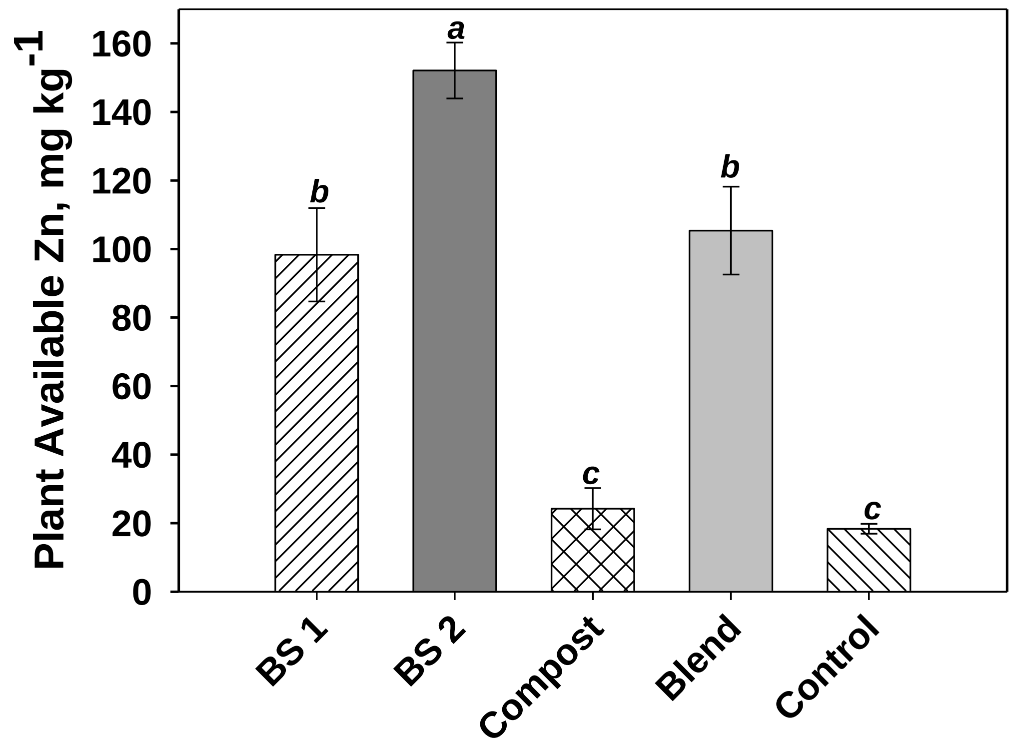


Fig. 16. Comparisons of Soil Respiration in amended and control soils.

Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

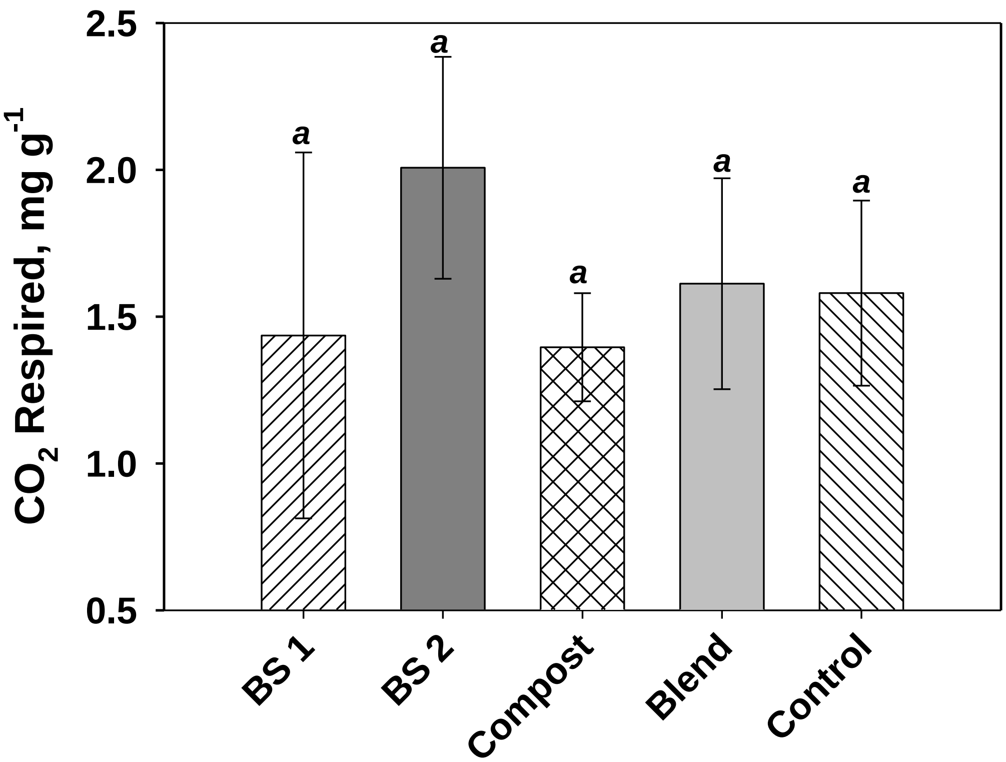


Fig. 17. Comparisons of above ground Plant Biomass (dry weight basis) in amended and control soils. Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD ($\alpha = 0.05$). Soil treatment abbreviations are defined in Figure 2.

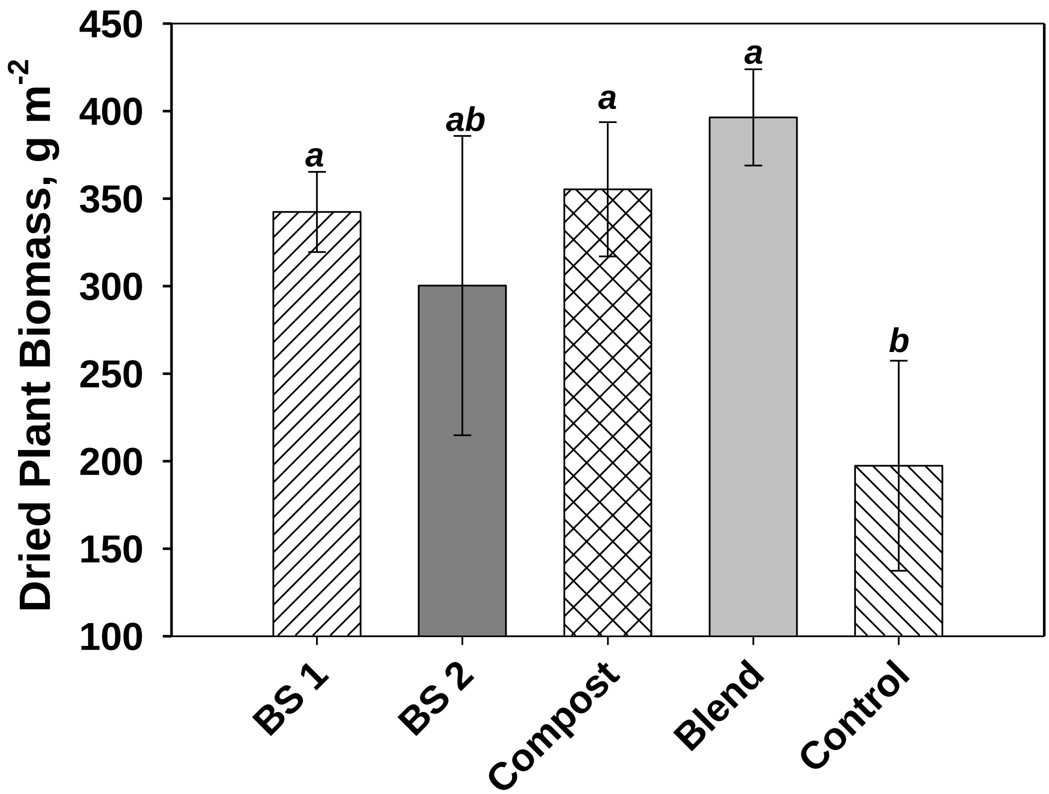


Fig. 18. Photos of vegetative growth on plots in 2016

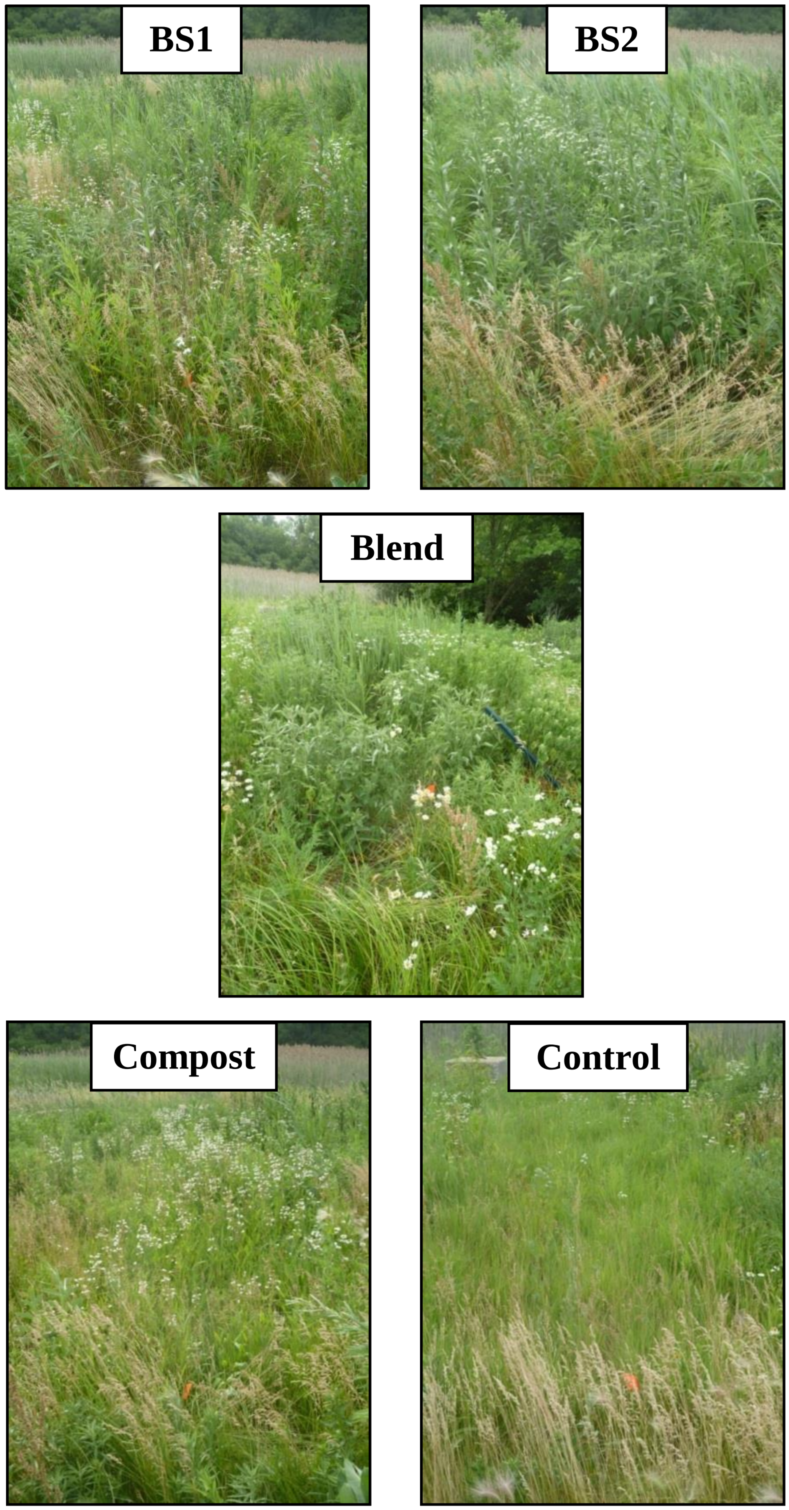


Fig. 19. Comparisons of Soil Cation Exchange Capacity in amended and control soils. Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

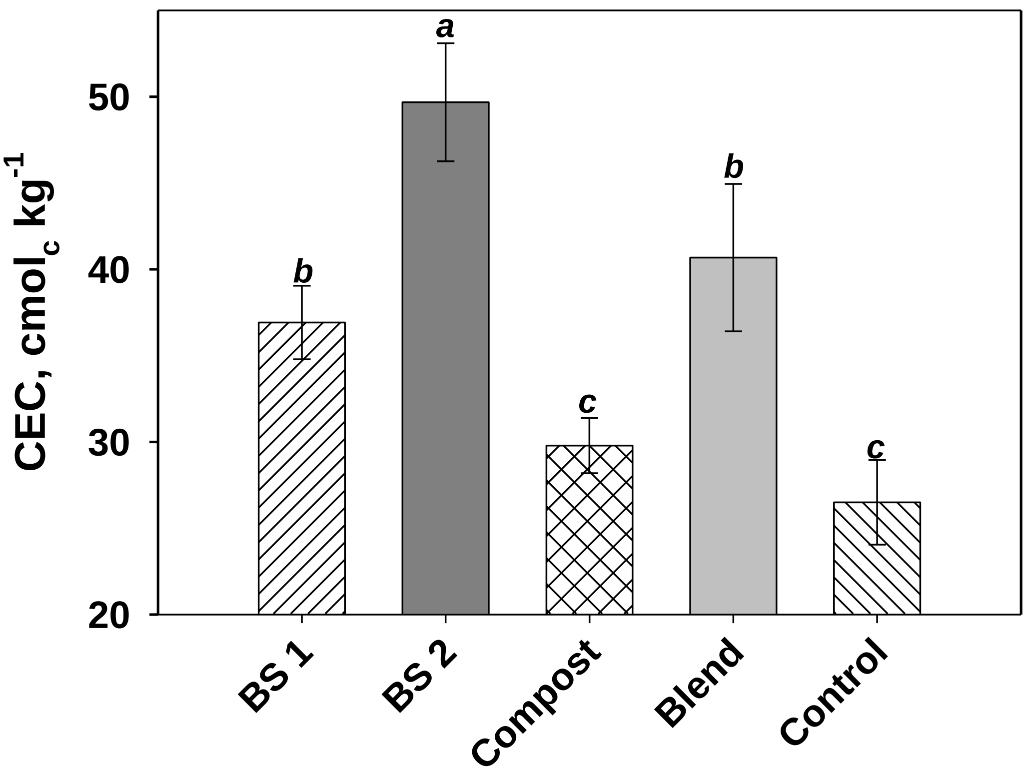


Fig. 20. Comparisons of Soil pH in amended and control soils.

Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

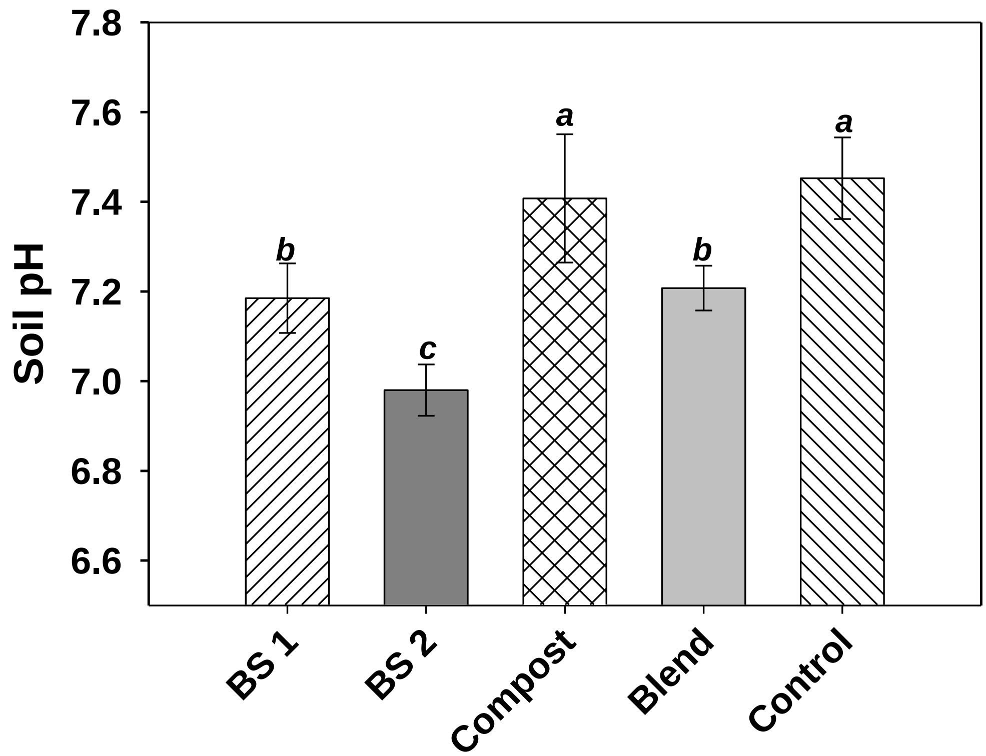


Fig. 21. Comparisons of Soil Salinity in amended and control soils.

Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

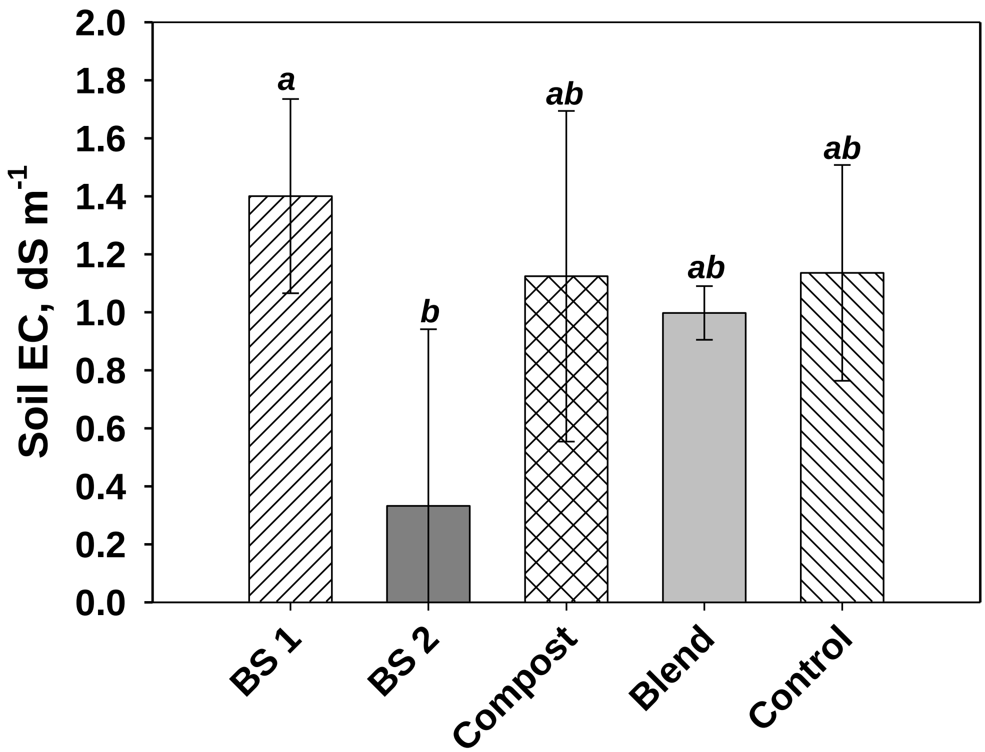


Fig. 22. Comparisons of Soil Zinc Concentration in amended and control soils. Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

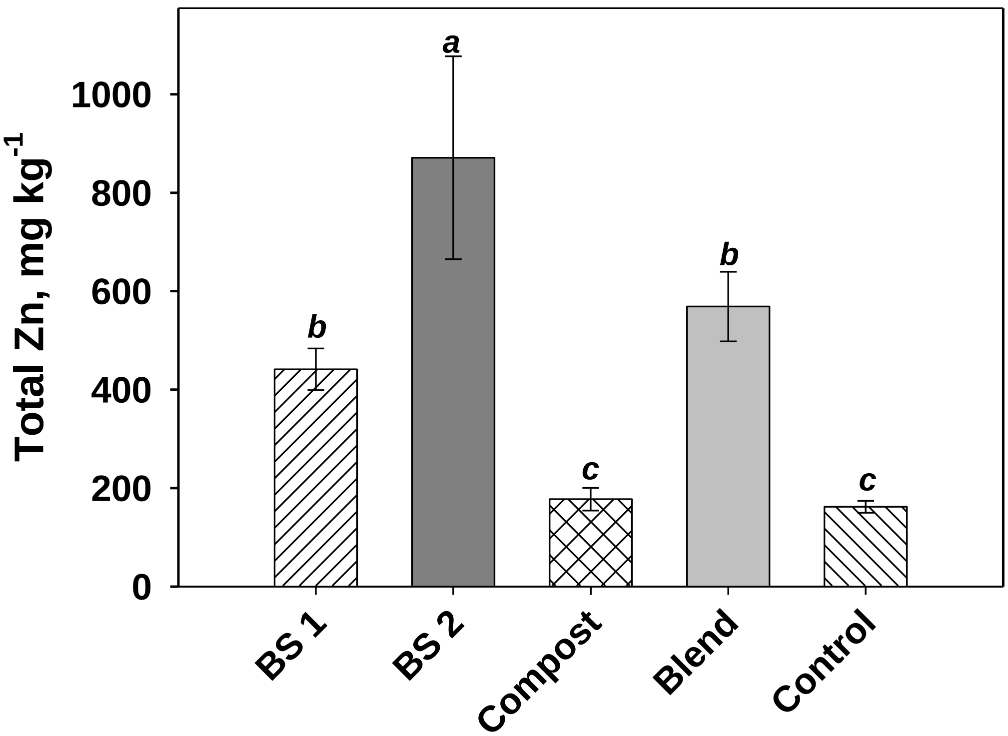


Fig. 23. Comparisons of Soil Copper Concentration in amended and control soils. Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

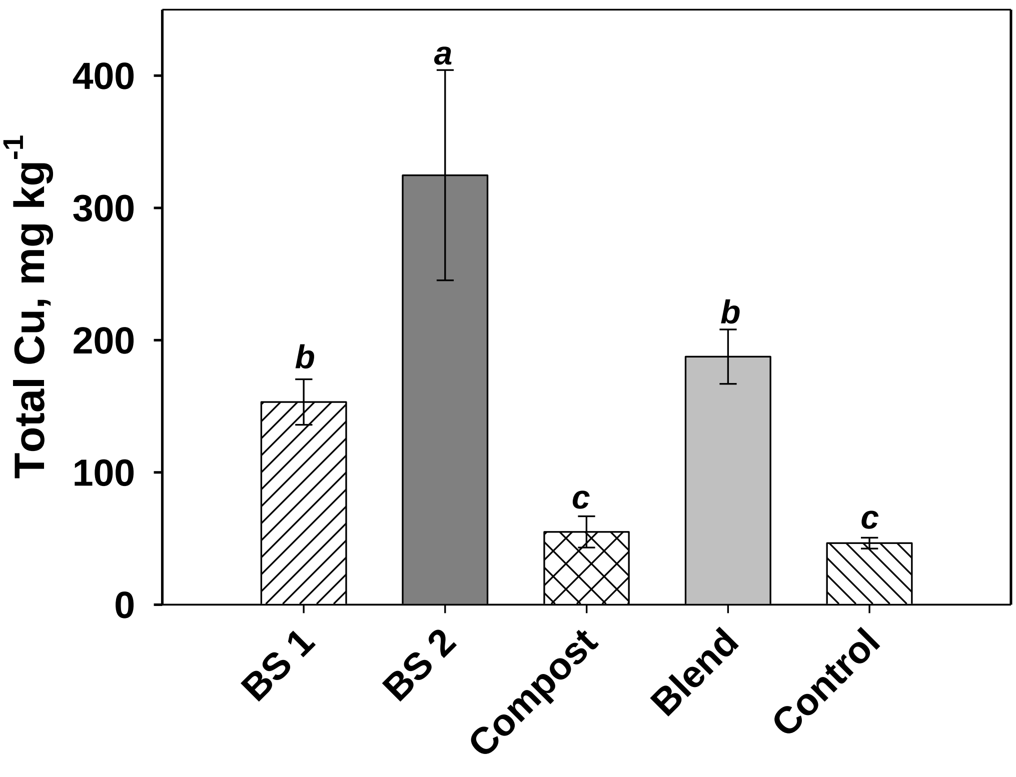


Fig. 24. Comparisons of Soil Lead Concentration in amended and control soils. Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD ($\alpha = 0.05$). Soil treatment abbreviations are defined in Figure 2.

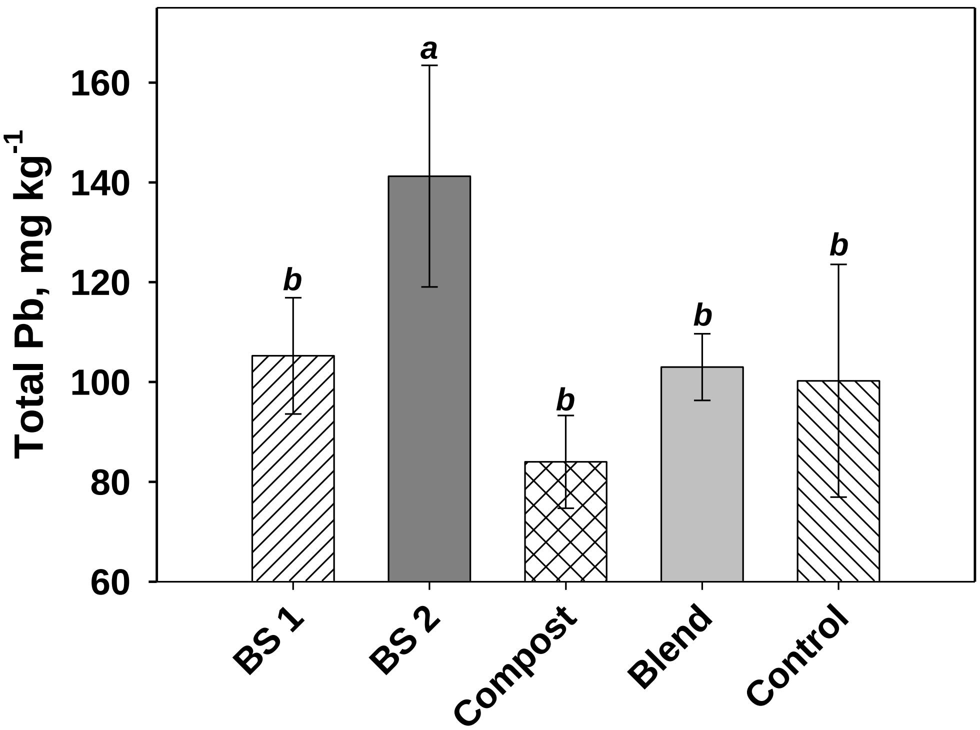


Fig. 25. Comparisons of Available Water Capacity in amended and control soils. Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

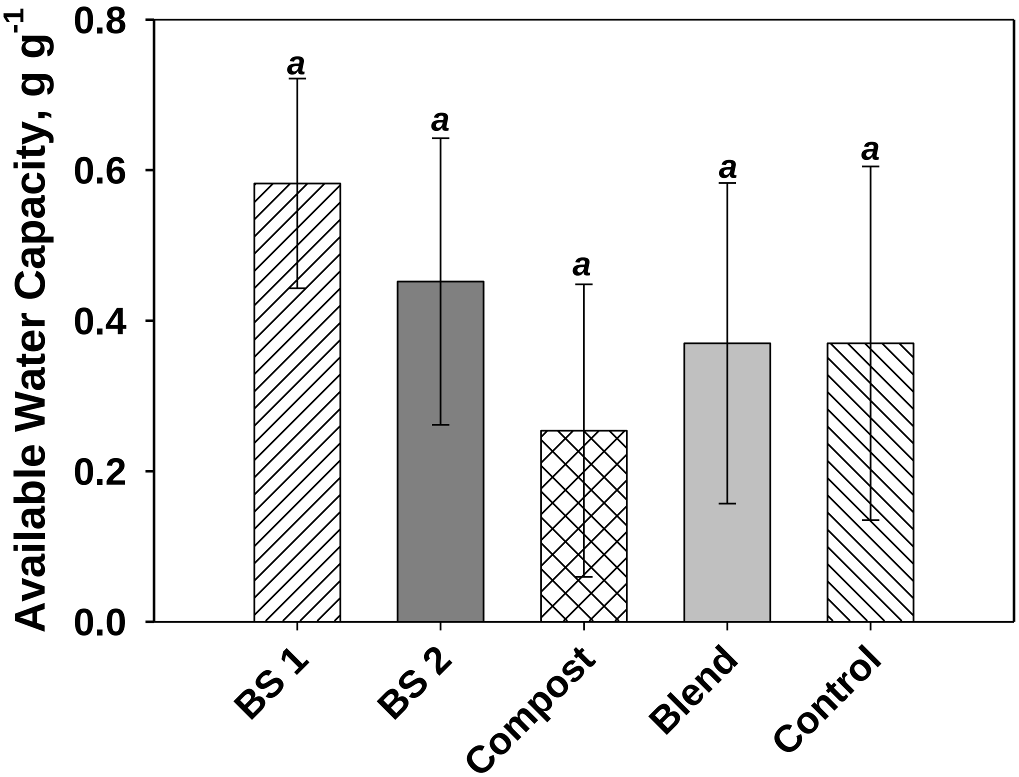


Fig. 26. Comparisons of Bulk Density in amended and control soils.

Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.

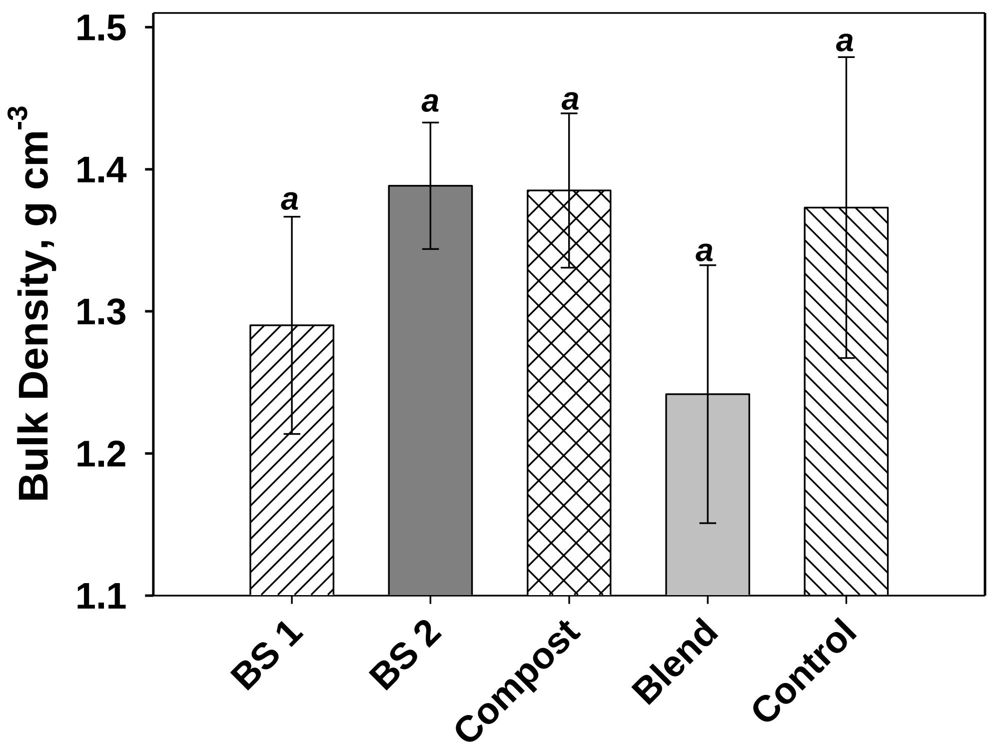
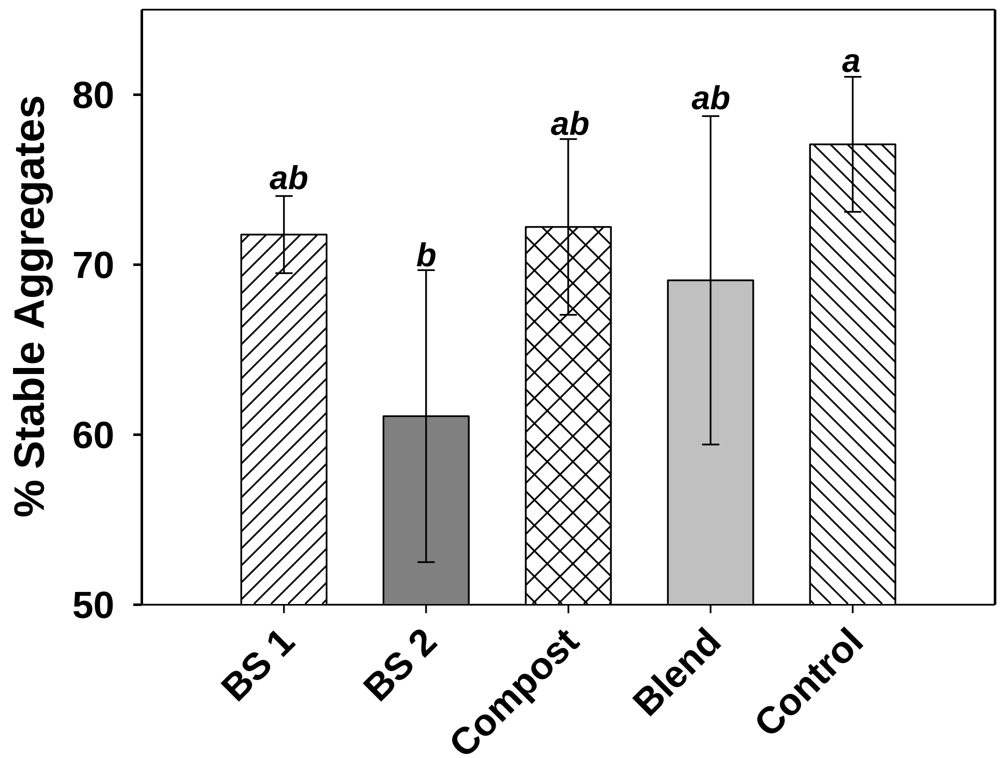


Fig. 27. Comparisons of Aggregate Stability in amended and control soils. Error bars represent 1 standard deviation and different letters represent significant difference between treatment means using Tukey's HSD (α = 0.05). Soil treatment abbreviations are defined in Figure 2.



Chapter 2:

Beneficial Reuse of Dredge Material in Manufactured Soil Blends: Soil Quality Parameter Assessments

ABSTRACT

Dredge material from the Cuyahoga River has many soil-like properties which makes it a great candidate for the main component in manufactured soil blends. This beneficial reuse of dredge is needed because it can no longer be traditionally disposed of by open-lake disposal. Blends were designed to compare the use of dredge to dredge fines, which is the smaller size fraction of dredge assumed to be unsuitable for reuse. They were also designed to assess the benefits of compost, clay and fertilizer additions. Results show that overall dredge fines blends led to greater soil quality and led to better yield, greater plant available water, total and active C, potentially mineralizable N, and micronutrients. The addition of a compost material also leads to better soil quality for a vast majority of the tested parameters. The dredge material contains > 50% sand, so the addition of clay expected to improve the blend quality. However, clay addition tended to decrease soil quality and plant yield in the blends. Furthermore, the addition of fertilizer did not aid plant growth as expected. It was found that the best performing blend included dredge fines, 20% compost, with no added clay or fertilizer.

INTRODUCTION

Dredging is a process in which sediments and debris that have compounded on the bottom of waterways is removed. This is a necessary practice to combat sedimentation- when sand and silt wash downstream and slowly fill channels. In the Cuyahoga River of Cleveland, Ohio, dredging is vitally important to maintain a clear navigational route for ships. Most of the sediment removed from the Cuyahoga, along with other Lake Erie access points such as Toledo Harbor, is disposed of by open-lake disposal (OEC, 2013). However, the Ohio EPA has stated that open-lake disposal negatively effects water quality in Lake Erie by contributing to the suspended sediment and phosphorus loads. Due to recent state legislation, by 2020 no dredged material may be disposed of into the open waters of Lake Erie (OEPA, 2015). Finding alternative uses for the dredged material is of high priority to meet upcoming legislation regulations and to help protect the water quality of Lake Erie.

This study was conducted to evaluate the beneficial reuse of dredge material in manufactured soil blends. For a material to be considered for use in a manufactured soil it must exhibit soil-like attributes such as plant nutrients, texture, and organic matter to contribute to soil quality and fertility (Dayton et al., 2010). To assess this, dredge and dredge fines were used to create the manufactured soil blends along with the addition of clay and compost. Dredge fines is the material separated by size fraction from the dredge, allegedly because the fine size fraction may contain more contaminants and is seen as unsuitable for reuse. To assess the soil health properties of the blends, multiple soil parameters were evaluated and a potted bioassay study was conducted to assess if vegetative growth was achievable.

Objectives

1. Compare dredge material versus dredge fines material on suitability in manufactured soil blends
2. Evaluate the effect of compost and clay additions in dredge blends
3. Assess if fertilizer addition is needed for plant growth on dredge blends

MATERIALS AND METHODS

Blends

The blend materials consisted of dredge material, compost, and clay. Dredge material was collected from the Cleveland Cuyahoga County Port Authority confined disposal facility 10B and 12, respectively referred to as dredge and dredge fines. Samples were air-dried and sieved to <2 mm. Two compost materials were evaluated in the blends. The first was leaf compost from Kurtz Bros., Inc. located in Cleveland, OH. The second was Com-Til from the City of Columbus Compost Facility. Com-Til is a composted product made from residual biosolids from Columbus wastewater treatment plants, yard waste, and wood chips. Clay used for the blends was “Blue Clay” from Kurtz Bros., Inc. Properties of each raw material was assessed (Table 5). There were 16 unique blends created for this study (Table 6). Materials were blended on a volume basis using a Kushlan 600-series electric mixer. The blends were developed to provide a range of texture and organic matter content using the following equations:

Total Sand (S) = (%Dredge S*Dredge proportion) + (%S in Clay/S*Clay/S proportion)

Total Silt (Si) = (%Dredge Si*Dredge proportion) + (%Si in Clay/S*Clay/S proportion)

Total Clay (C) = (%Dredge C*Dredge proportion) + (%C in C/Sand*C/Sand proportion)

Soil Properties

The following soil properties were evaluated for the raw blend materials (Table 5) and blends (Table 7, 8, 9): plant available water (PAW), total organic C, active C, plant available N (PAN), potentially mineralizable N (PMN), soil pH, soil salinity, and plant available nutrients. Materials and methods for all properties can be found in Chapter 1 (excluding plant available water and N). Plant available water is the soil moisture available for plant uptake and is the difference between container capacity and permanent wilting point. Plant available water was determined using the dwarf sunflower wilt method (Cassel & Nielsen, 1986). Plant available N was found in the form of ammonium (NH_4-N) and nitrate (NO_3-N), and determined using potassium chloride (KCl) extraction followed by colorimetric analysis (Maynard & Kalra, 1993).

Bioassay

A greenhouse bioassay was conducted with blends potted in 4.5 in x 6 in plastic pots and planted (1 g seed per plot) with annual ryegrass (*Lolium multiflorum*). The ryegrass was grown for 30 d with an average of 1.25 in simulated rainfall per week supplied (Dayton et al., 2016). Each blend was potted with 8 replicates: 4 unfertilized reps and 4 fertilized reps. Miracle-Gro fertilizer (15-30-15) was applied to fertilized reps 7 and 14 days after initial planting resulting in a total of 100 mg N kg^{-1}, 87 mg P kg^{-1}, and 100 mg K kg^{-1} applied to the pots (Dayton et al., 2016). After 30 days of growth, the grass was harvested and dried at 60°C, with weights taken afterwards to determine yield. After harvest, physical measures were taken of the soil including container capacity and bulk density. Container capacity and bulk density is described in Chapter 1. Container capacity was then used to calculate plant available water.

Statistical Analysis

Data was statistically analyzed using Minitab Version 17 (Released 2016) for Windows. One-way analysis of variance (ANOVA) was conducted comparing dredge blends to dredge fines blends. If the populations were different ($P < 0.05$), ANOVA and multiple means comparisons were conducted by Tukey honestly significant difference (HSD) for the populations separately. If the populations were not different ($P > 0.05$) , ANOVA and multiple means comparisons were conducted by Tukey honestly significant difference (HSD) for all blends together. The level of significance for all statistical comparisons was α=0.05.

RESULTS AND DISCUSSION

Bioassay

Yield

After a 30 d bioassay, the dry weight of the harvested rye grass growth was taken (Fig. 28; Table 7). The results show that dredge fines blends > dredge blends ($P<0.002$). The largest yield of 3.11 g was seen in dredge fines blend 80:0:20 (Com-Til) (Fig. 28; Table 7). The largest yield for a dredge blend was 2.43 g in the 80:0:20 (compost) blend. These results suggest that clay addition does not aid yield, and 20% compost material addition to dredge fines material produces the best yield results. Fertilizer addition only caused a significant increase in yield for 2 of the 16 total blends (Fig. 28; Table 7). In a similar study done by Basta & Dayton (2006) assessing rye grass yield in manufactured soil blends, yield ranges from 2.97 to 3.16 g which is comparable to this studies yield range of 1.23 to 3.11 g.

Bulk Density

Bulk density was dredge blends > dredge fines blends at $P < 0.001$ (Fig. 29; Table 7). The lower bulk density values for dredge fines blends were unexpected due to the dredge fines having 11% clay compared to 7% clay in the dredge raw material (Table 6). The largest bulk density value was 1.43 g cm^{-3} in dredge blend 50:50:0. The smallest bulk density values were found in dredge fines blends and ranged from 1.12-1.16 g cm^{-3} and in general were in blends with 20% Com-Til (Fig. 29; Table 7). As expected, the addition of a compost material lowered the bulk density, and in general this trend was seen when either compost or Com-Til was added to any of the dredge or fines blends (Fig. 29; Table 7). Similarly, the addition of clay tended to increase the bulk density of the blends. According to Brady & Weil (1996), a bulk density lower than 1.6 g cm^{-3} is recommended, therefore all blends bulk densities were acceptable. A typical mineral soil bulk density is 1.25 g cm^{-3} (Brady & Weil, 1996), with both dredge and dredge fines blends with < 40% added clay and 20% added compost nearest to this value.

Container Capacity

Results for container capacity showed dredge fines blends > dredge blends at $P < 0.001$ (Fig. 30; Table 7). The largest container capacity values ranged from 0.31-0.32 g g^{-1} in the fines blends 100:0:0, 80:0:20 (compost), and 80:0:20 (Com-Til) (Fig. 30; Table 7). The smallest value for container capacity was 0.17 g g^{-1} in dredge blend 70:30:0. This suggests that the blends that hold the most water are composed of dredge fines, no additional clay, and 20% added composted material.

Plant Available Water

Plant available water (PAW) results (Fig. 31; Table 8) are very similar to container capacity results. Dredge fines blends > dredge blends at $P < 0.001$. PAW did not vary in any of the dredge blends and all dredge means were lower than the recommended value of 0.2 g g^{-1} (Gugino et al., 2009) (Fig. 31; Table 8). The largest PAW value was 0.26 g g^{-1} for dredge fines blend 80:0:20 (Com-Til) (Fig. 31; Table 8). Clay addition tended to decrease PAW, and compost versus Com-Til additions were comparable. These results suggest that the blends with the greatest plant available water are composed of dredge fines, no additional clay, and 20% composted material. These results were surprising considering the greater sand content of the dredge fines, however the sands may be acting similar to silt due to its finer texture to lead to the greater water holding capacity.

Carbon

Total Organic Carbon

Dredge fines blends > dredge blends for total organic C (Fig. 32; Table 8). This was expected due to the raw material total organic C contents for dredge (13.6 g kg^{-1}) was less than that of fines (22.2 g kg^{-1}) (Table 5). In general, the blends with no added compost material were lower than the recommended total organic C value of 23.3 g kg^{-1} (Gugino et al., 2009). Com-Til (283 g kg^{-1}) blends were expected to show larger total organic C than compost (148 g kg^{-1}) blends, however this trend was not seen. The blends with greatest total organic C (32.3-36.2 g kg^{-1}) all were composed of 20% compost (Fig. 32; Table 8).

Active Carbon

Active C results show dredge fines blends > dredge blends at $P < 0.001$ (Fig. 33; Table 8). The largest active C was 412 mg kg^{-1} in dredge fines blend 48:32:20 (compost). The addition of compost increased active C significantly for dredge blends to levels comparable to that of the dredge fines blends. Com-Til did not show as large of an increase to active C (Fig. 33; Table 8). These results are expected because compost raw material (1219 mg kg^{-1}) has greater active C than Com-Til (784 g kg^{-1}) (Table 5). However, no blend resulted in adequate active C (550 mg kg^{-1}) according to Gugino et al. (2009). The active C results help explain the unexpected results for total organic C that compost addition leads to greater active C and organic C than Com-Til. The Com-Til has larger organic C but less active C (Table 5) because it has gone through a longer composting process causing the readily-available active C to be consumed by microbes. These results suggest that the best blend for C content is composed of dredge fines and 20% compost with no change with clay addition.

Nitrogen

Plant Available Nitrogen

Dredge blends > dredge fines blends for PAN at $P < 0.001$(Fig. 34; Table 8). This trend is consistent with the PAN in the raw dredge material (81.7 mg kg^{-1}) and raw dredge fines material (7.93 mg kg^{-1}) (Table 5). The PAN results for the dredge fines blends did not significantly vary (Table 8). PAN tended to decrease with clay addition (Fig. 31; Table 8). The greatest PAN (102 mg kg^{-1}) was in the dredge blends 80:0:20 (compost), however compost versus Com-Til additions did not significantly differ in PAN results in the blends. Johnson et al. (2000) recommends 100-150 mg kg^{-1} for rye grass growth, and nearly all of the blends PAN did not fall within this range. However, even with slightly deficient PAN in the blends, proper yield still resulted.

Potentially Mineralizable Nitrogen

The trend for PMN is dredge fines blends > dredge blends at $P < 0.001$ (Fig. 35; Table 8) which is consistent with the PMN in the raw dredge fines (6.76 mg g^{-1}) and raw dredge (3.40 mg g^{-1}) (Table 5). The addition of clay tended to decrease PMN in the blends, however not significantly (Fig. 35; Table 8). The greatest PMN was in the dredge fines blend 80:0:20 (compost), with compost addition tending to show greater PMN than Com-

Til in the blends (Fig. 35; Table 8). The blends with no added compost material tended to not be above the recommended PMN value of 6.00 mg g^{-1} (Gugino et al., 2009). The N results give conflicting suggestions for blend materials, with PAN greatest in dredge blends but PMN greater in dredge fines blends. The N results do tend to agree that additional clay decreases PAN and PMN, and compost is more favorable than Com-Til.

Soil pH and Salinity

Soil pH results were dredge fines blends > dredge blends at $P < 0.001$ and ranged from 7.28 to 7.48. (Fig. 36; Table 8). Daniels et al. (2007) showed land applied dredge with compost addition had soil pH results ranging from 6.8 to 7.4, similar to this study's findings. These results are expected due to the dredge (7.37) having a lower pH compared to the dredge fines (7.43) (Table 5). Significant variance was not seen between the dredge fines blends. In general, as clay addition increased the soil pH increased in the blends (Fig. 36; Table 10). The addition of Com-Til (6.78) was expected to decrease soil pH, however this was not seen (Fig. 36; Table 8). The preferred soil pH for rye grass growth falls between 5.5-7.0 (Johnson et al., 2000), therefore the blends are slightly alkaline and could inhibit plant growth.

Soil salinity was not significantly different between the dredge and dredge fines blends for $P < 0.05$ (Fig. 34; Table 8). Clay addition to the blends also did not show a consistent trend. The addition of Com-Til (9.24 dS m^{-1}) was expected to increase soil salinity compared to the compost (3.64 dS m^{-1}) (Table 5). This result was seen in some blends such as the highest EC (1.91 dS m^{-1}) occurring in dredge fines blend 64:16:20 (Com-Til) (Fig. 37; Table 8), however a significant increase in all blends was not seen. Johnson et al. (2000) recommends a soil EC value < 5.00 dS m^{-1} for rye grass growth, and all blends were below this value.

Nutrients

Macronutrients

Plant available P did not show a significant difference between dredge blends compared to dredge fines blends at $P < 0.05$ (Fig. 38; Table 9). This was expected due to dredge (47.0 mg kg^{-1}) having similar P levels to the dredge fines (44.8 mg kg^{-1}) (Table 5). Clay addition did not show a significant effect on plant available P (Table 9). As expected, compost material addition to the blends did significantly increase plant available P. Com-Til (2178 mg kg^{-1}) has much more P than the compost (239 mg kg^{-1}) (Table 5). This correlated to the trend seen in the blends with Com-Til based blends having significantly higher plant available P (95.6-106 mg kg^{-1}) than the compost blends (55.6-68.1 mg kg^{-1}) (Fig. 38; Table 9). All blends with added compost material had adequate P of 32.5 mg kg^{-1} for rye grass growth (Johnson et al., 2000), and are below the surface water quality standard of 200 mg P kg^{-1} (Sharpley et al., 1996) . Similar to these results, land applied dredge materials were shown to have moderate levels of P not in excess (Daniels et al., 2007).

Similar to P results, plant available K did not show a significant difference between dredge blends and dredge fines blend at $P < 0.05$ (Fig. 39; Table 9). In fact, the blends that contained only raw dredge/fines material and clay resulted in the lowest plant available K (Fig. 39; Table 9), with clay addition not showing a trend in the blends. Blends with no added compost material resulted in K levels lower than the adequate value of 150 mg kg^{-1} (Johnson et al., 2000). Compost and Com-til both had >2000 mg kg^{-1} of plant available K (Table 5), however the blends with 20% compost (505-659 mg kg^{-1}) had significantly greater K than blends with 20% Com-Til (251-299 mg kg^{-1}) (Table 9).

Secondary Nutrients

Plant available Ca was not significantly different between dredge and dredge fines blends at $P < 0.05$ (Fig. 40; Table 9). All blends had adequate Ca for rye grass growth of at least 375 mg kg^{-1} (Johnson et al., 2000). Plant available Mg and S results were dredge blends > dredge fines blend (Figures 41&42; Table 9). Plant available S results were expected because dredge (470 mg kg^{-1}) has much greater plant available S than dredge fines (183 mg kg^{-1}) (Table 5). Clay addition only appeared to positively affect availability of Mg in the blends (Fig. 41; Table 9). The addition of a compost material lead to an increase of plant available Mg, however did not show a significant difference between the two materials of compost versus Com-Til (Fig. 41; Table 9). Both S and Mg in the blends were well above adequate for rye grass growth (Johnson et al., 2000). Similar results were seen in Daniels et al. (2007) that essential micronutrients were all at adequate levels.

Micronutrients

The micronutrients assessed were plant available Fe, Cu, Mn, and Zn (Figures 43-46; Table 10). The trend dredge fine blends > dredge blends ($P < 0.001$) was seen for all micronutrients (Figures 43-46; Table 10), however all micronutrients were adequate in the blends (Johnson et al., 2000). Clay addition tended to cause a decrease in availability of Fe and Zn (Fig. 43; Fig. 46; Table 10). Compost material addition did not appear to effect micronutrient availability. The addition of Com-Til (176 mg Zn kg^{-1}) was expected to cause greater plant available Zn compared to compost (26.1 mg kg^{-1}), however a significant increase did not result in the blends.

CONCLUSIONS

Although dredge fines are assumed to be unfit for beneficial reuse, the results of this study show otherwise. Manufactured soil blends containing dredge fines had better soil health for multiple parameters compared to blends containing dredge. Dredge fines blends led to better yield, greater plant available water, total and active C, potentially mineralizable N, and were more abundant in many soil micronutrients. The dredge did outcompete the dredge fines for plant available N, however neither material led to adequate levels. Overall both compost and Com-til performed well in the blends to lead to better soil quality for a vast majority of the tested parameters. However, compost outperformed Com-til in the blends for plant available N, potentially mineralizable N, active C and total C. Daniels et al. (2007) also recommends the addition of a compost material to dredge to manufacture a blend that results in proper yield. The addition of clay was expected to aid plant growth and soil quality by altering the texture of the blends from a sandy loam to a loam/silty clam loam texture. This effect was not seen, and in fact as clay addition increased in the blends soil quality decreased for a majority of the parameters tested. It is possible that although the dredge materials had a sandy texture, the sands were very fine and acted as a silt for the soil properties. This could explain why adding clay didn’t lead to the expected improvements to soil quality properties. Fertilizer addition did not lead to an increase in plant yield as expected. From these findings, it can be concluded that the ideal blend will include dredge fines, 20% compost, with no added clay or fertilizer.

Table 5. Selected Properties of Raw Materials of Blends

Parameter	**Cleveland Dredge**	**Cleveland Dredge Fines**	**Clay**	**Leaf Compost**	**Com-Til**
Textural Class	SL	SL	C	-	-
pH	7.37	7.43	7.49	7.27	6.78
EC dS m^{-1}	1.22	1.00	1.49	3.64	9.24
TOC g kg^{-1}	13.6	22.2	15.1	148	283
Active C mg kg^{-1}	-	-	-	1219	784
Total C	-	-	-	16.8	30.1
PAN mg kg^{-1}	81.7	7.93	9.20	-	-
PMN mg g^{-1}	3.40	6.76	-	-	-
P mg kg^{-1}†	47.0	44.8	1.26	239	2178
K mg kg^{-1}	93.2	126	116	>2000	>2000
Ca g kg^{-1}	2.74	2.76	3.46	4.41	4.56
Mg mg kg^{-1}	223	171	202	681	872
S mg kg^{-1}	470	183	375	139	1947
Fe mg kg^{-1}	383	407	233	235	193
Cu mg kg^{-1}	4.94	11.6	2.98	2.74	2.92
Mn mg kg^{-1}	37.6	96.6	50.8	70.4	30.5
Zn mg kg^{-1}	19.5	30.0	2.54	26.1	176

†Mehlich-3 plant available nutrients

Table 6. Dredge Blend properties and composition

Material	Ratio ID	Composition Ratio: Dredge	Composition Ratio: Clay	Composition Ratio: Composted Material	Sand	Clay	Textural Class
		%					
Dredge	100:0:0†	100	0	0	68.0	7.00	SL
Dredge	70:30:0	70	30	0	48.5	24.4	SCL
Dredge	50:50:0	50	50	0	35.5	36.0	CL
Dredge	80:0:20	80	0	20*	68.0	7.00	SL
Dredge	56:24:20	56	24	20*	48.5	24.4	SCL
Dredge	40:40:20	40	40	20*	35.5	36.0	CL
Dredge	80:0:20	80	0	20**	68.0	7.00	SL
Dredge Fines	100:0:0	100	0	0	59.0	11.0	SL
Dredge Fines	80:20:0	80	20	0	47.8	21.8	L
Dredge Fines	60:40:0	60	40	0	36.6	32.6	CL
Dredge Fines	80:0:20	80	0	20*	59.0	11.0	SL
Dredge Fines	64:16:20	64	16	20*	47.8	21.8	L
Dredge Fines	48:32:20	48	32	20*	36.6	32.6	CL
Dredge Fines	80:0:20	80	0	20**	59.0	11.0	SL
Dredge Fines	64:16:20	64	16	20**	47.8	21.8	L
Dredge Fines	48:32:20	48	32	20**	36.6	32.6	CL

*Compost

**Com-Til

†Results are on a volume/volume basis

Modified from Dayton et al. (2016)

Table 7. Mean values of Post- Bioassay Data in Dredge and Dredge Fines Blends

Dredge Blends	Bulk Density† g cm^{-3}		Container Capacity† g g^{-1}		Rye Grass Yield† g		
100:0:0	1.30	bcd	0.19	cd	F‡	2.02	abc
					U‡	1.82	abcde
70:30:0	1.40	ab	0.17	d	F	2.27	ab
					U	1.32	de
50:50:0	1.43	a	0.18	cd	F	1.39	cde
					U	1.23	e
80:0:20*	1.23	d	0.21	a	F	2.43	a
					U	1.71	bcde
56:24:20*	1.25	cd	0.22	a	F	1.95	abcd
					U	1.65	bcde
40:40:20*	1.34	abc	0.20	ab	F	1.90	abcde
					U	1.78	abcde
80:0:20**	1.26	cd	0.20	bc	F	2.05	abc
					U	1.97	abcd
100:0:0	1.12	b	0.32	a	F	2.65	ab
					U	2.00	ab
80:20:0	1.28	a	0.25	ef	F	2.18	ab
					U	1.81	b
60:40:0	1.29	a	0.24	f	F	1.90	ab
					U	1.71	b
80:0:20*	1.15	b	0.31	a	F	2.15	ab
					U	2.46	ab
64:16:20*	1.18	ab	0.28	bc	F	1.86	ab
					U	2.12	ab
48:32:20*	1.21	ab	0.30	ab	F	2.10	ab
					U	1.98	ab
80:0:20**	1.14	b	0.31	a	F	3.11	a
					U	2.18	ab
64:16:20**	1.14	b	0.28	cd	F	2.26	ab
					U	1.90	ab
48:32:20**	1.16	b	0.26	de	F	1.58	b
					U	1.80	b

*Compost **Com-Til

† Means within column/blend material with same letter are not different ($\alpha = 0.05$). Dredge vs. dredge fines are significantly different ($P < 0.05$).

‡ Fertilized (F) with 15-30-15 Miracle-Gro or Unfertilized (U)

Table 8. Mean values of soil properties of Dredge and Dredge Fines Blends

Blend	PAW† g g^{-1}	TOC† g kg^{-1}	Active C† mg kg^{-1}	PAN† mg kg^{-1}	PMN† mg g^{-1}	Soil pH†	EC‡ dS m^{-1}
<u>Dredge</u>							
100:0:0	0.13 a	13.6 d	36.6 d	81.7 ab	3.40 b	7.37 bc	1.22 ef
70:30:0	0.15 a	15.6 d	117 cd	53.1 ab	2.82 b	7.37 bc	0.91 g
50:50:0	0.13 a	13.9 d	77.3 cd	35.3 b	2.31 b	7.43 ab	1.81 ab
80:0:20*	0.18 a	26.3 b	386 a	102 a	9.27 a	7.28 d	1.35 e
56:24:20*	0.16 a	32.3 a	268 b	77.9 ab	9.49 a	7.35 cd	1.01 fg
40:40:20*	0.17 a	24.4 b	303 ab	45.4 ab	9.24 a	7.45 a	1.63 bc
80:0:20**	0.16 a	20.9 c	160 c	71.7 ab	7.89 a	7.35 cd	1.68 bc
<u>Dredge Fines</u>							
100:0:0	0.24 abcd	22.2 fg	282 bcd	7.93 a	6.76 e	7.43 a	1.00 fg
80:20:0	0.21 cd	24.4 ef	306 abcd	23.6 a	5.75 ef	7.47 a	1.21 ef
60:40:0	0.19 d	20.3 g	215 d	7.53 a	4.44 f	7.38 a	1.71 abc
80:0:20*	0.25 ab	36.2 a	371 ab	17.7 a	13.5 a	7.42 a	1.58 cd
64:16:20*	0.25 abc	34.8 ab	375 ab	15.1 a	11.5 bc	7.47 a	1.37 de
48:32:20*	0.20 d	36.0 a	412 a	32.2 a	12.0 ab	7.47 a	1.30 e
80:0:20**	0.26 a	28.5 cd	340 abc	38.7 a	11.4 bc	7.44 a	1.82 ab
64:16:20**	0.23 abcd	31.6 bc	340 abc	40.1 a	9.96 cd	7.48 a	1.91 a
48:32:20**	0.20 bcd	27.2 de	249 cd	23.1 a	9.41 d	7.45 a	1.68 abc
Adequate	0.2¶	23.3¶	550¶	100 to 150§	6.00¶	5.5-7.0§	<5.00§

* Compost

** Com-Til

† Means within column/blend material with same letter are not different ($\alpha = 0.05$). Dredge vs. dredge fines are significantly different ($P < 0.001$).

‡ Means within column with same letter are not different ($\alpha = 0.05$). Dredge vs. dredge fines are not significantly different ($P < 0.05$).

§ Johnson et al., 2000

¶ Gugino et al., 2009

Table 9. Mean values of Macro and Secondary Nutrients in Dredge and Dredge Fines Blends

Blend	P‡		K‡		Ca‡		Mg†		S†	
	mg kg^{-1}									
Dredge										
100:0:0	47.0	cdef	93.2	e	2741	ab	223	c	470	c
70:30:0	35.7	fg	110	e	2562	abc	238	bc	531	bc
50:50:0	29.3	g	117	e	2544	abc	255	b	490	c
80:0:20*	64.3	b	505	c	2458	c	263	b	501	bc
56:24:20*	60.7	bcd	553	bc	2436	c	263	b	468	c
40:40:20*	55.6	bcde	584	b	2635	abc	293	a	580	ab
80:0:20**	106	a	264	d	2571	abc	216	c	636	a
Dredge Fines										
100:0:0	44.8	defg	126	e	2758	ab	171	d	183	d
80:20:0	40.5	efg	129	e	2607	abc	193	cd	275	bc
60:40:0	33.4	fg	123	e	2535	abc	194	cd	381	a
80:0:20*	68.1	b	571	b	2777	a	234	ab	170	d
64:16:20*	62.4	bc	535	bc	2449	c	228	ab	221	cd
48:32:20*	65.8	b	659	a	2525	bc	248	a	224	cd
80:0:20**	95.6	a	251	d	2620	abc	211	bc	293	b
64:16:20**	104	a	280	d	2529	bc	240	ab	383	a
48:32:20**	98.1	a	299	d	2639	abc	257	a	424	a
Adequate§	32.5		150		375		20		5.0 to 7.5	

* Compost

** Com-Til

† Means within column/blend material with same letter are not different ($\alpha = 0.05$). Dredge vs. dredge fines are significantly different ($P < 0.001$).

‡ Means within column with same letter are not different ($\alpha = 0.05$). Dredge vs. dredge fines are not significantly different ($P < 0.05$).

§ Johnson et al., 2000

Table 10. Mean values of Select Micronutrients in Dredge and Dredge Fines Blends

Blend	**Fe†**		**Cu†**		**Mn†**		**Zn†**	
	mg kg^{-1}							
Dredge								
100:0:0	383	a	4.94	b	37.6	d	19.5	ab
70:30:0	336	cd	5.79	a	43.7	c	17.0	bc
50:50:0	316	de	5.39	ab	49.7	b	14.9	c
80:0:20*	353	bc	5.40	ab	39.6	d	20.3	ab
56:24:20*	324	de	5.14	b	45.8	c	18.1	bc
40:40:20*	308	e	5.41	ab	54.2	a	17.4	bc
80:0:20**	371	ab	5.28	ab	45.6	c	22.1	a
Dredge Fines								
100:0:0	407	a	11.6	a	96.6	ab	30.0	a
80:20:0	383	bc	10.6	b	96.0	ab	25.3	bc
60:40:0	356	d	9.07	e	88.2	c	19.4	d
80:0:20*	368	cd	10.1	bc	92.0	bc	26.8	ab
64:16:20*	370	cd	9.68	cde	93.7	b	23.0	c
48:32:20*	354	d	9.21	de	91.7	bc	22.6	cd
80:0:20**	389	ab	10.5	bc	99.2	a	28.1	ab
64:16:20**	380	bc	10.2	bc	94.4	ab	28.6	a
48:32:20**	369	cd	9.90	bcd	95.4	ab	25.1	bc
Adequate	4.5§				≤50¶		2.00§	

* Compost

** Com-Til

† Means within column/blend material with same letter are not different ($\alpha = 0.05$). Dredge vs. dredge fines are significantly different ($P < 0.001$).

§ Johnson et al., 2000

¶ Gugino et al., 2009

Fig. 28. Rye Grass Yield Results for Dredge Blends and Dredge Fines Blends

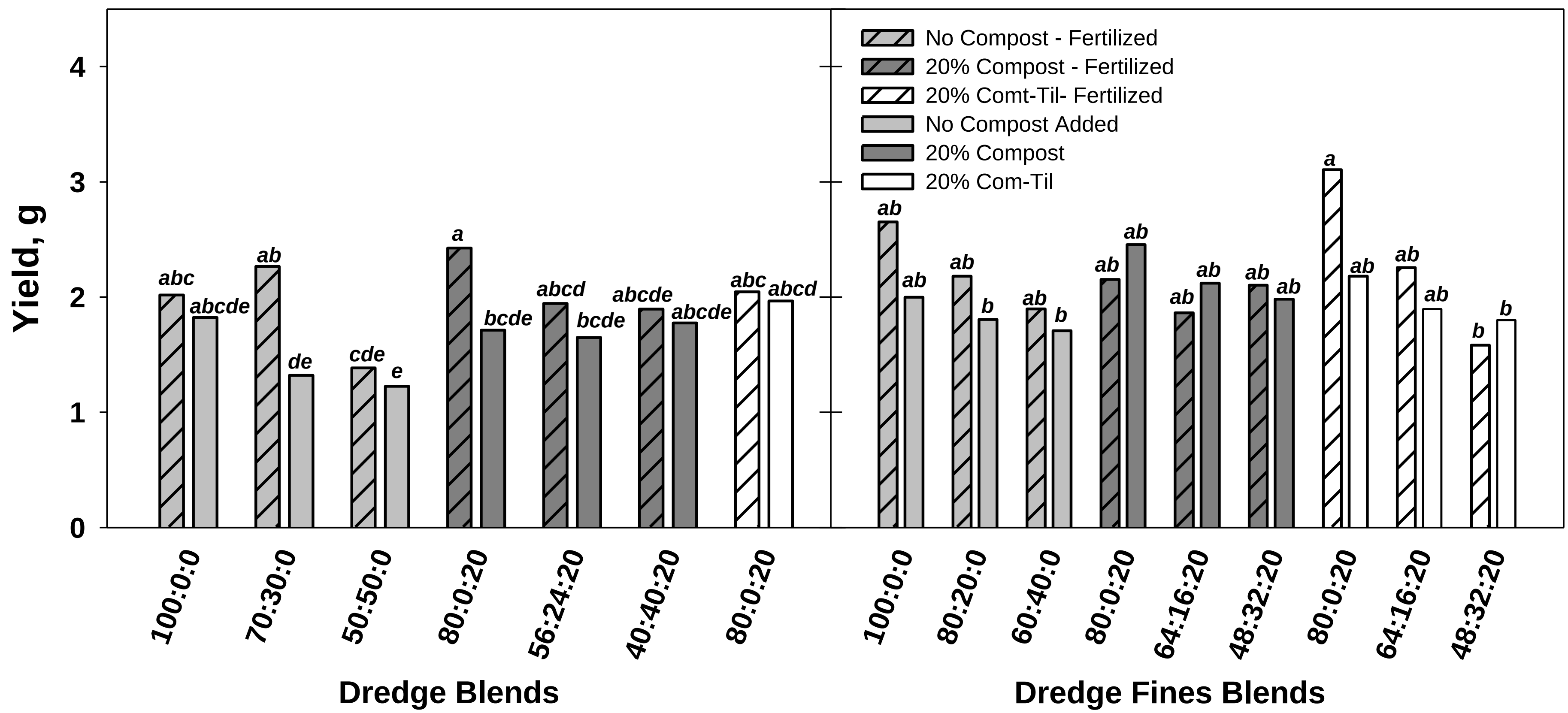


Fig. 29. Bulk Density Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD ($\alpha = 0.05$). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

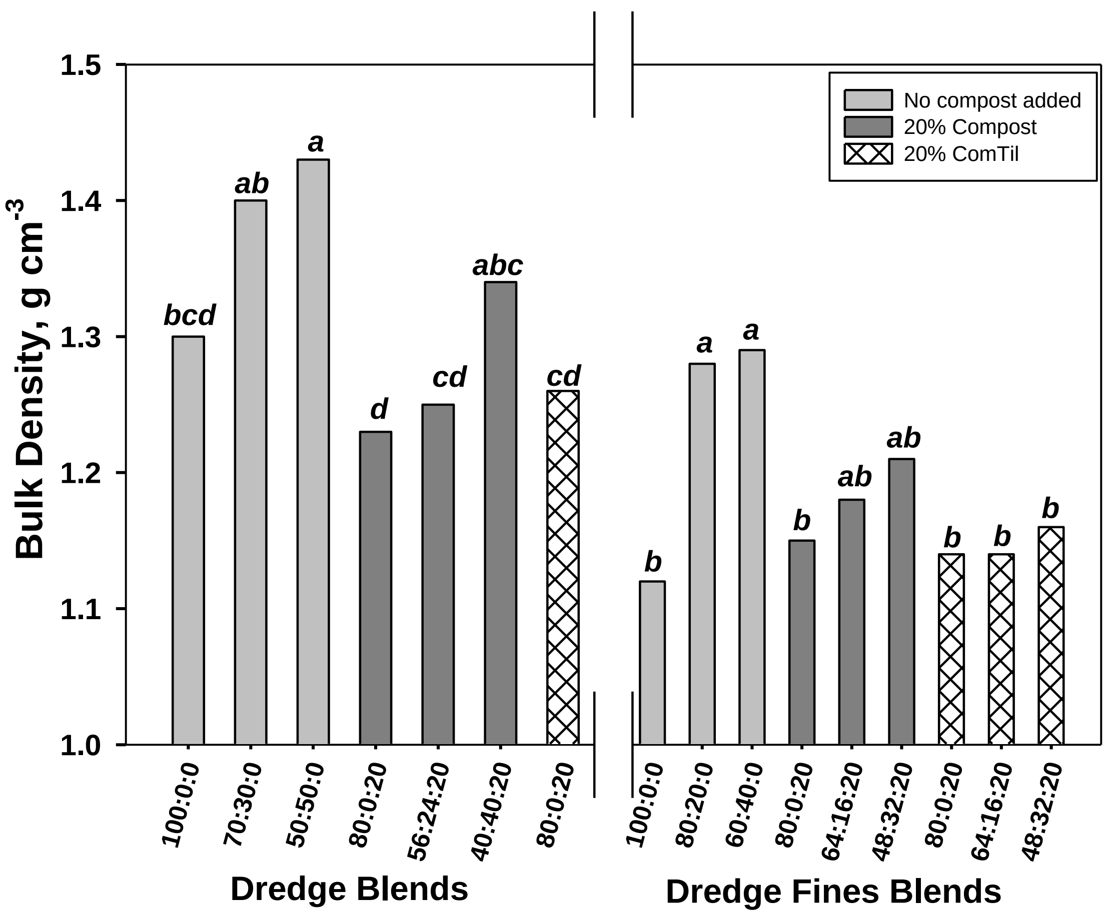


Fig. 30. Container Capacity Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD ($\alpha = 0.05$). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

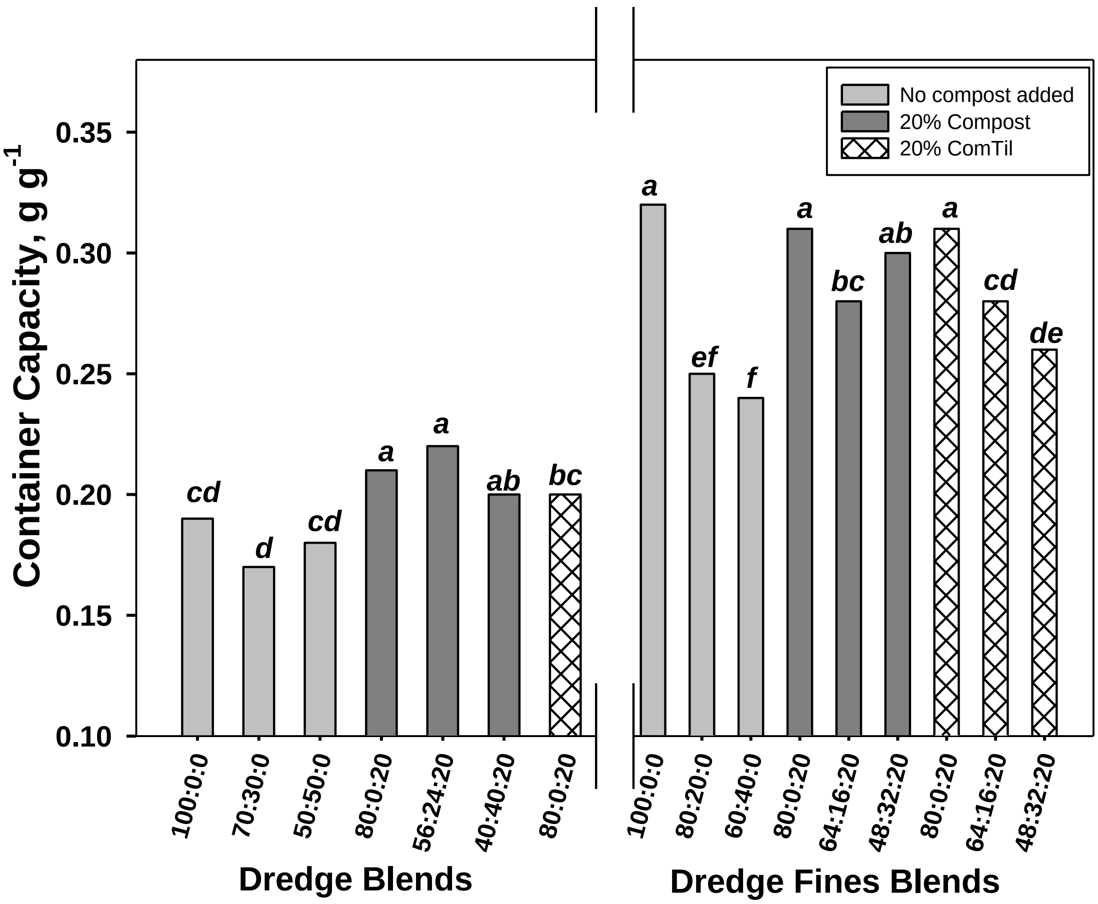


Fig. 31. Mean Plant Available Water of Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD ($\alpha = 0.05$). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

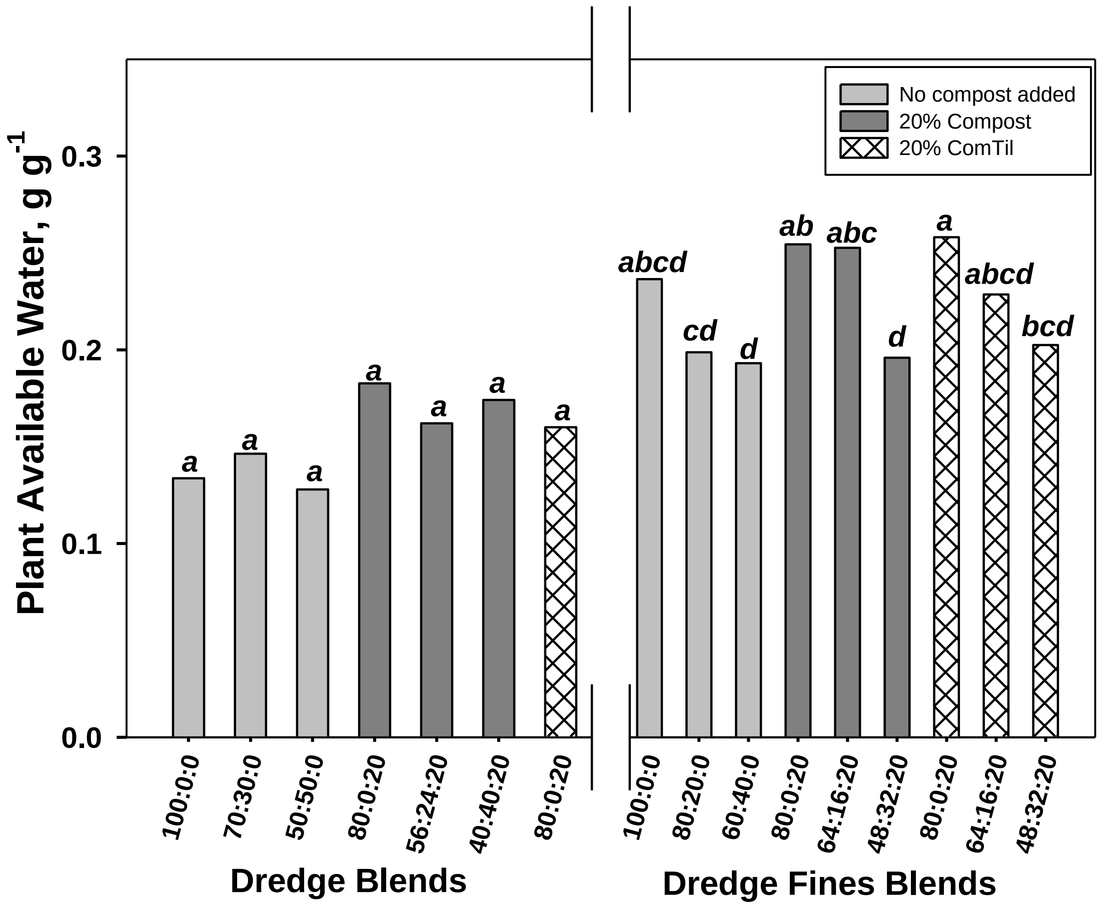


Fig. 32. Mean Total Organic Carbon Results for Dredge Blends and Dredge Fines Blends Different letters represent significant difference between blend means using Tukey's HSD ($\alpha = 0.05$). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

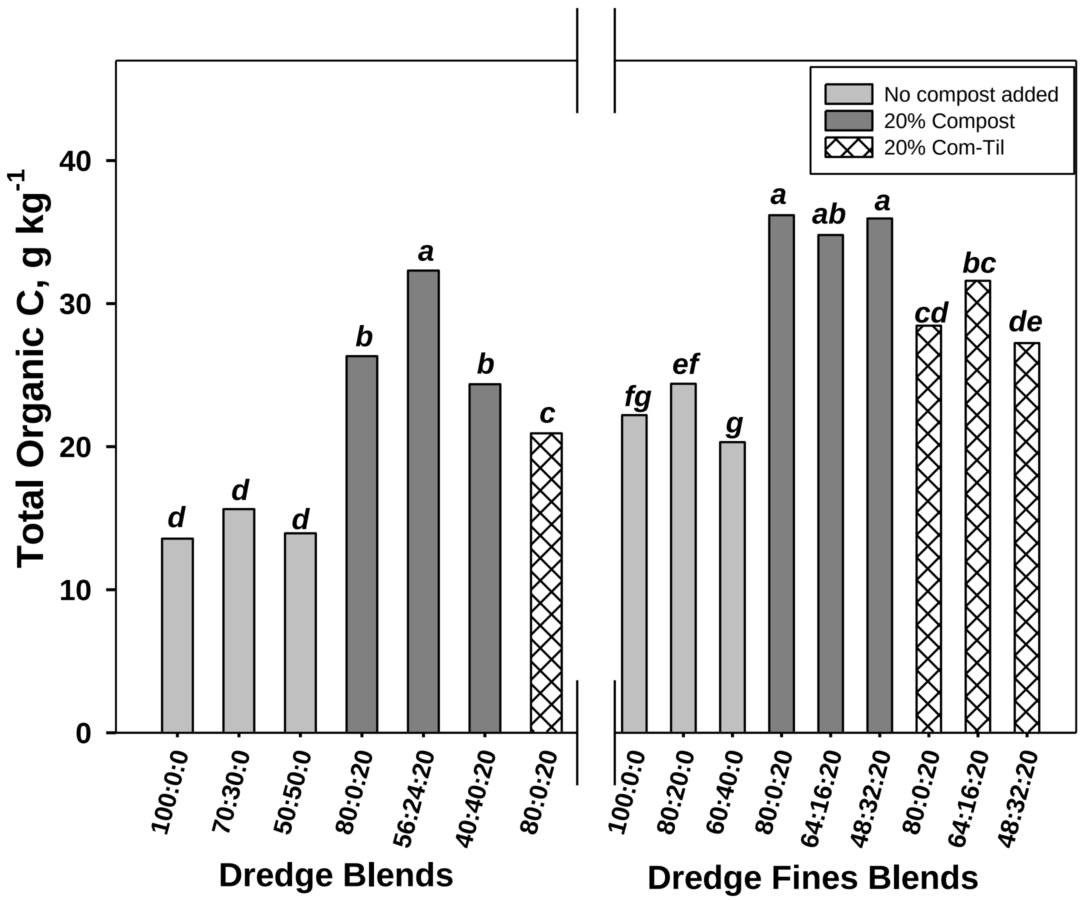


Fig. 33. Mean Active Carbon Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD ($\alpha = 0.05$). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

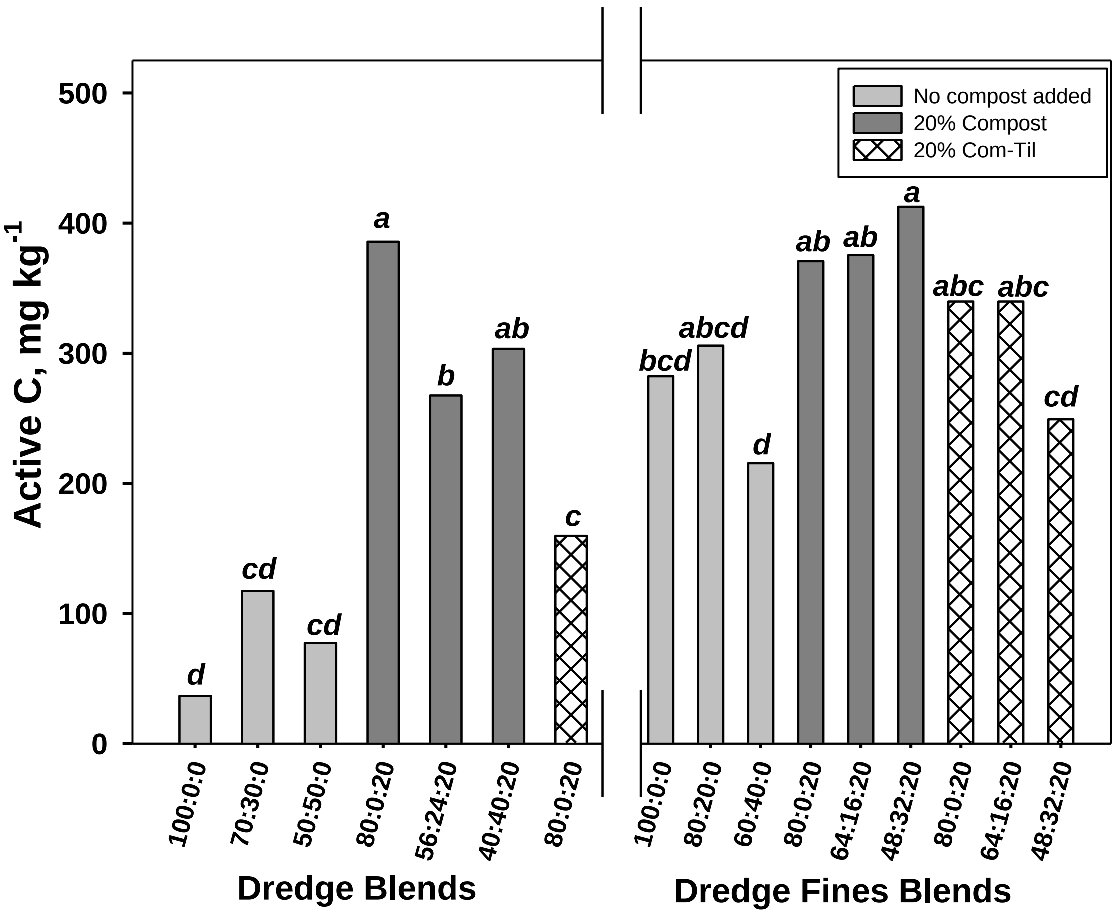


Fig. 34. Mean Plant Available Nitrogen Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD (α = 0.05). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

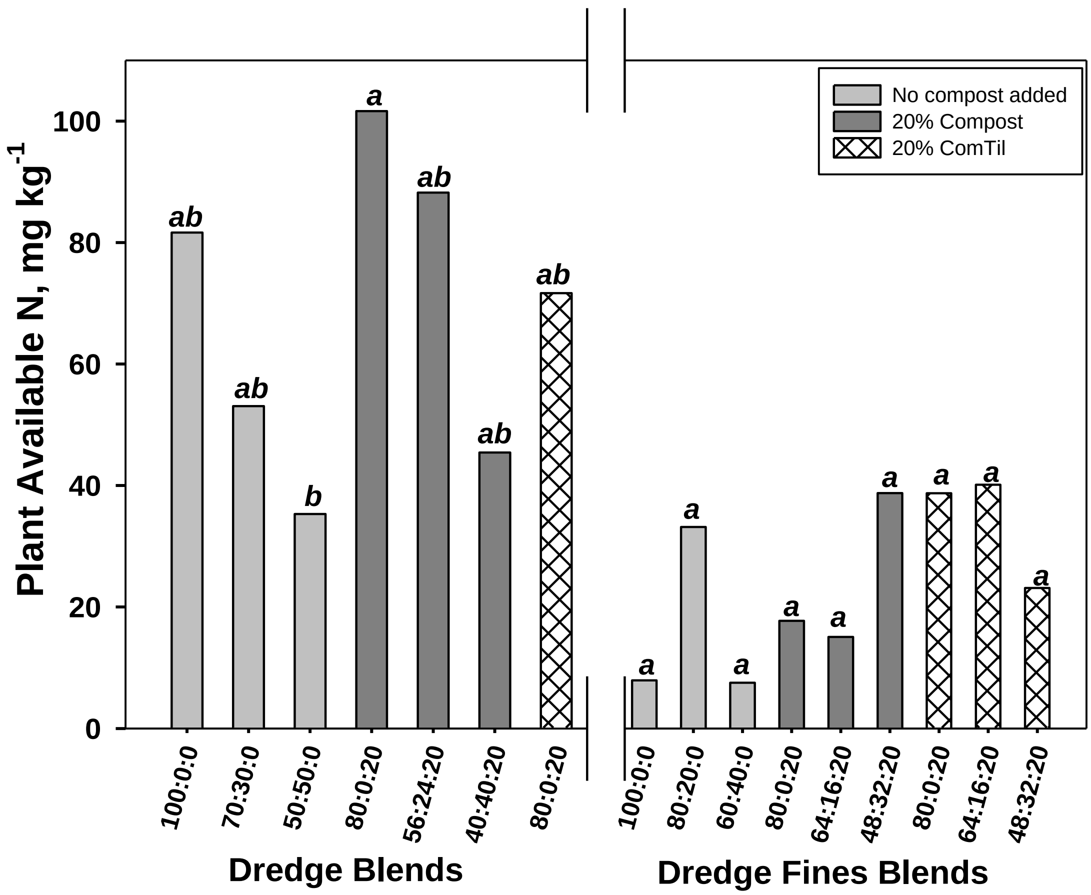


Fig. 35. Mean Potentially Mineralizable Nitrogen Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD (α = 0.05). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

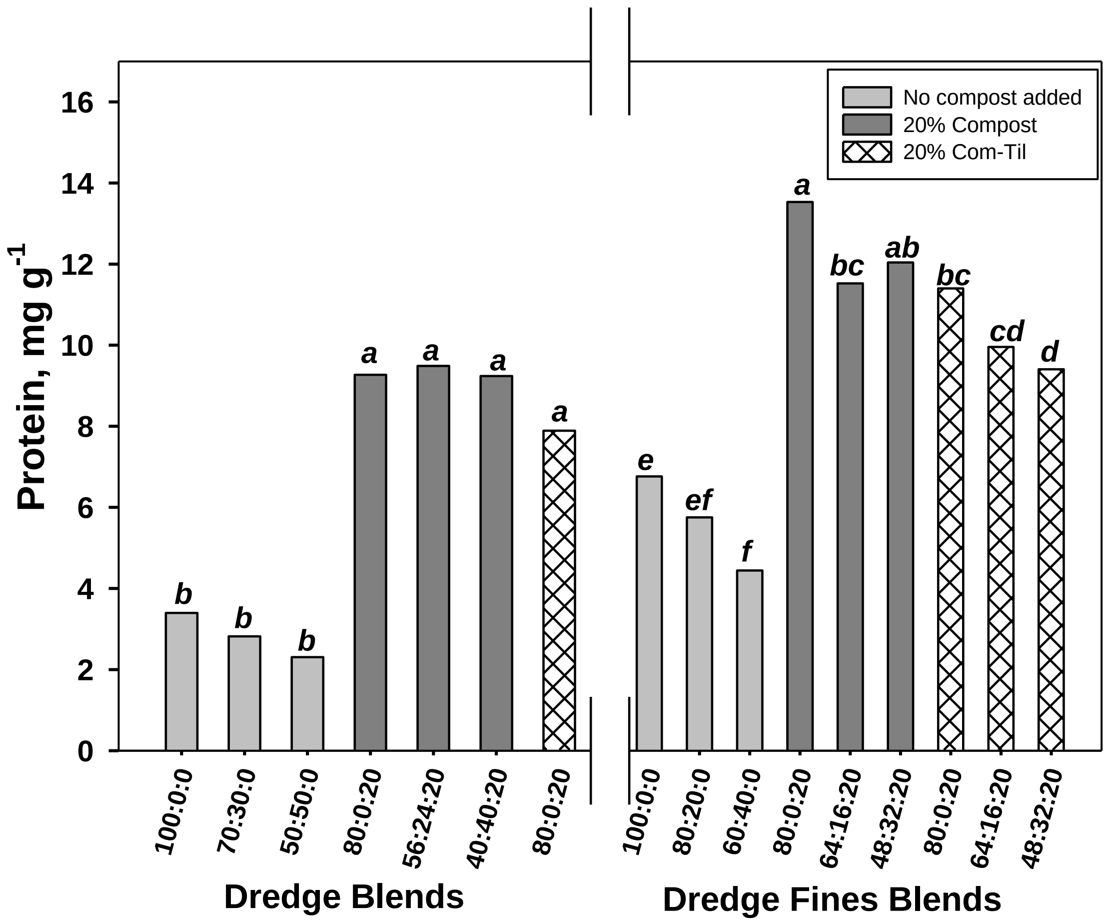


Fig. 36. Mean Soil pH Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD (α = 0.05). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

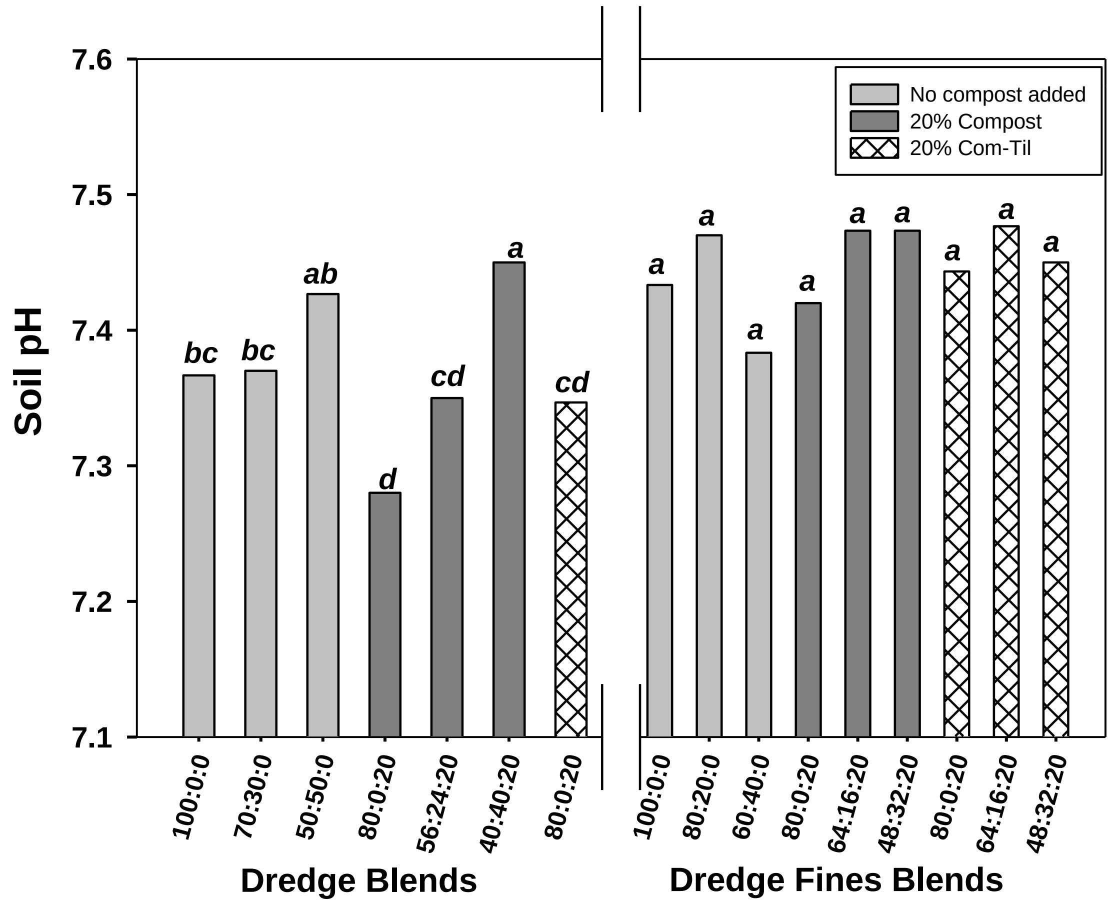


Fig. 37. Mean Soil Salinity Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD ($\alpha = 0.05$) for all blends.

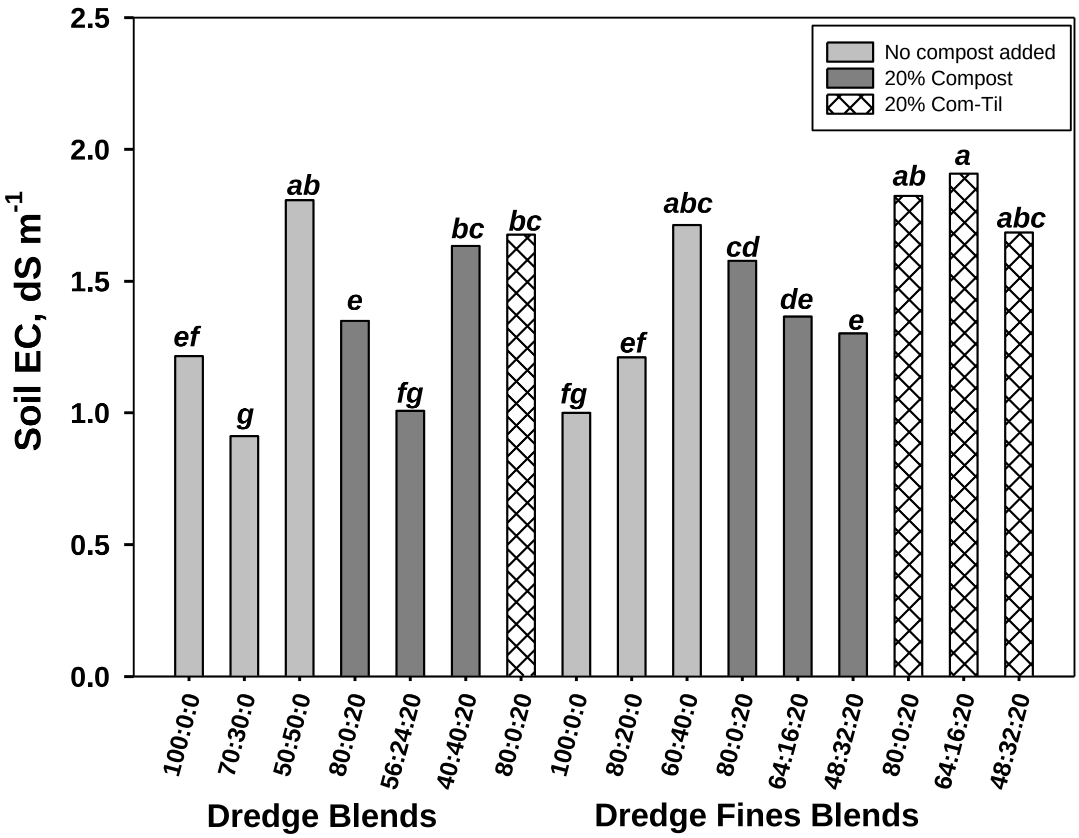


Fig. 38. Mean Plant Available Phosphorus Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD ($\alpha = 0.05$) for all blends.

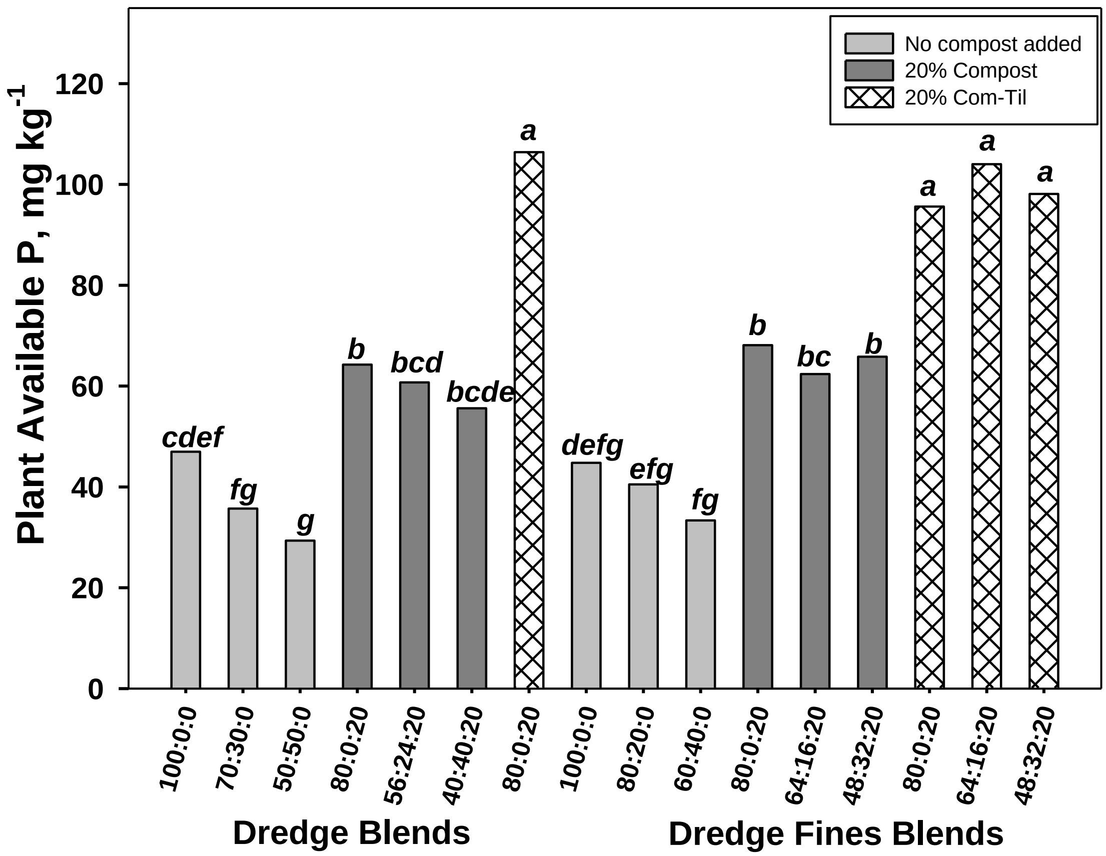


Fig. 39. Mean Plant Available Potassium Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD (α = 0.05). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

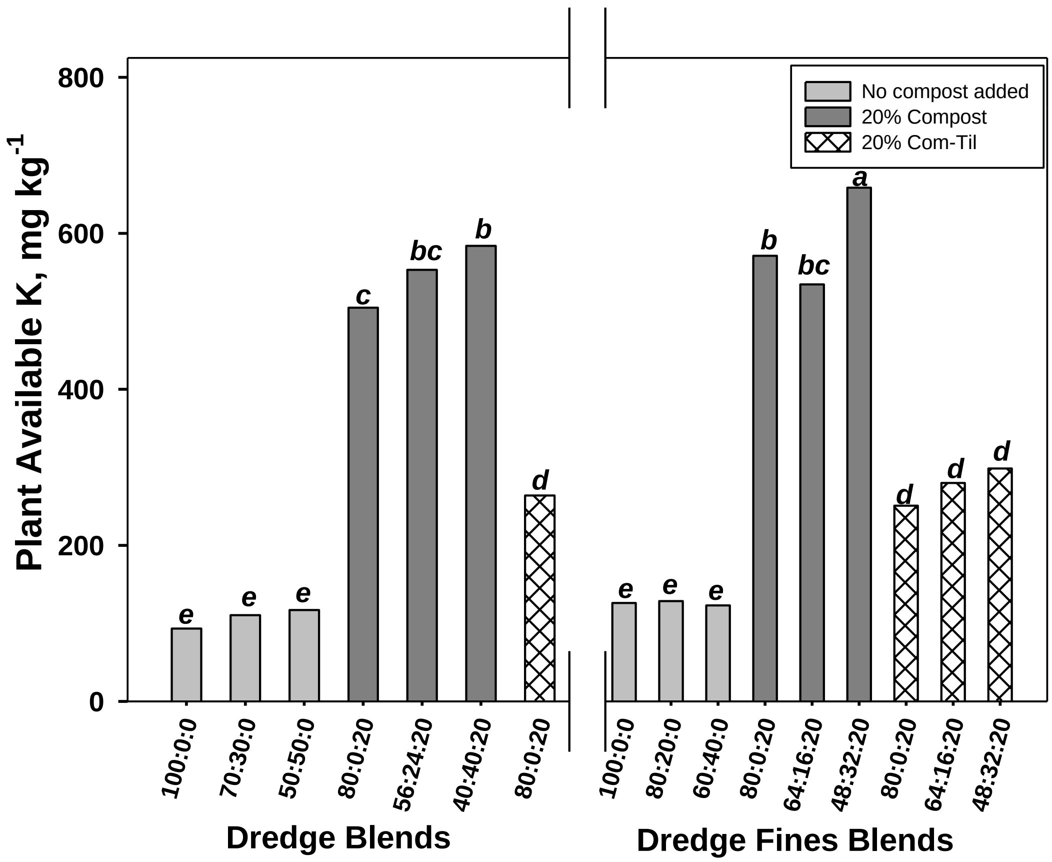


Fig. 40. Mean Plant Available Calcium Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD ($\alpha = 0.05$) for all blends.

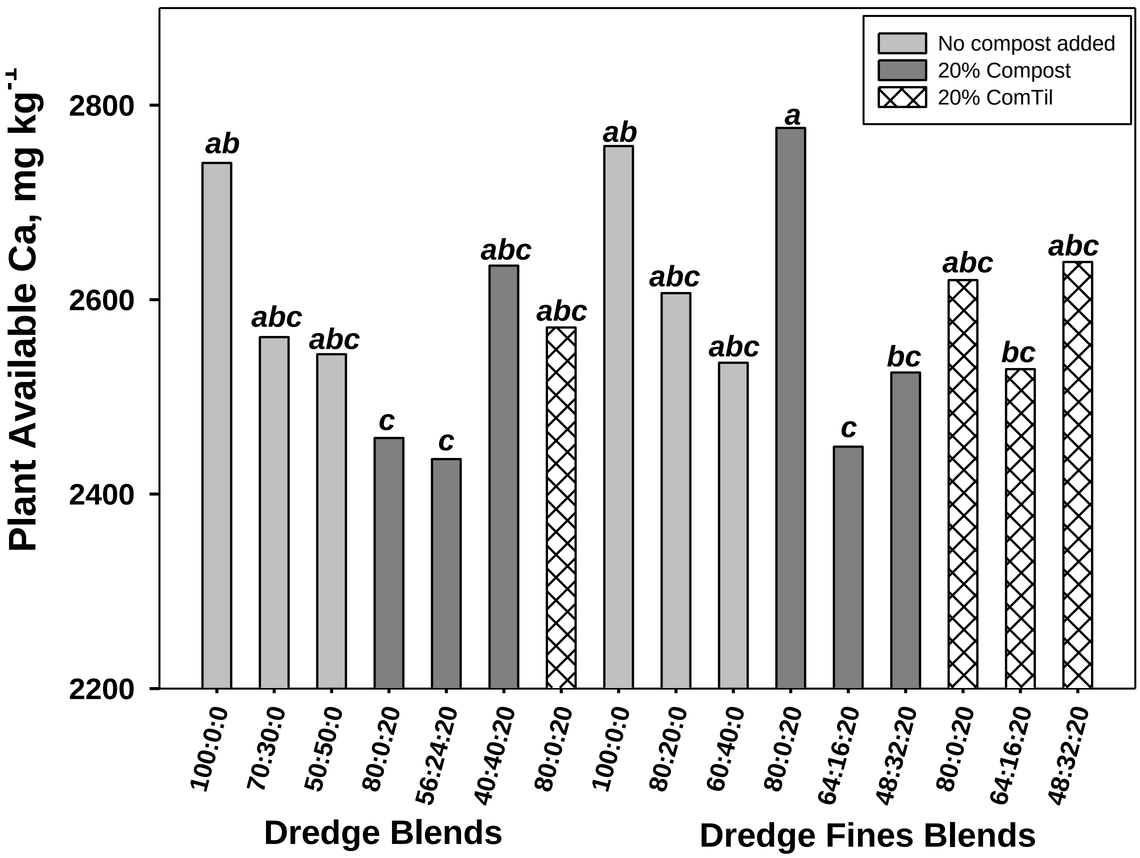


Fig. 41. Mean Plant Available Magnesium Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD ($\alpha = 0.05$). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

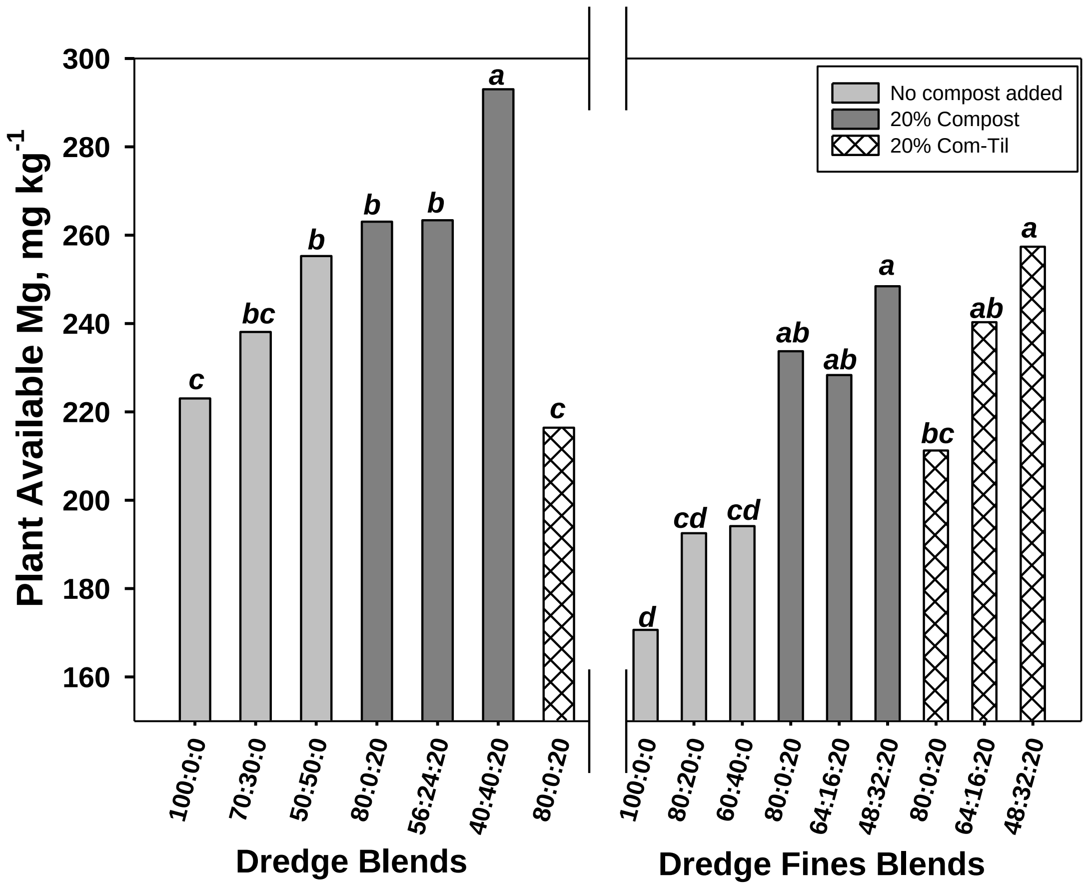


Fig. 42. Mean Plant Available Sulfur Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD (α = 0.05). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

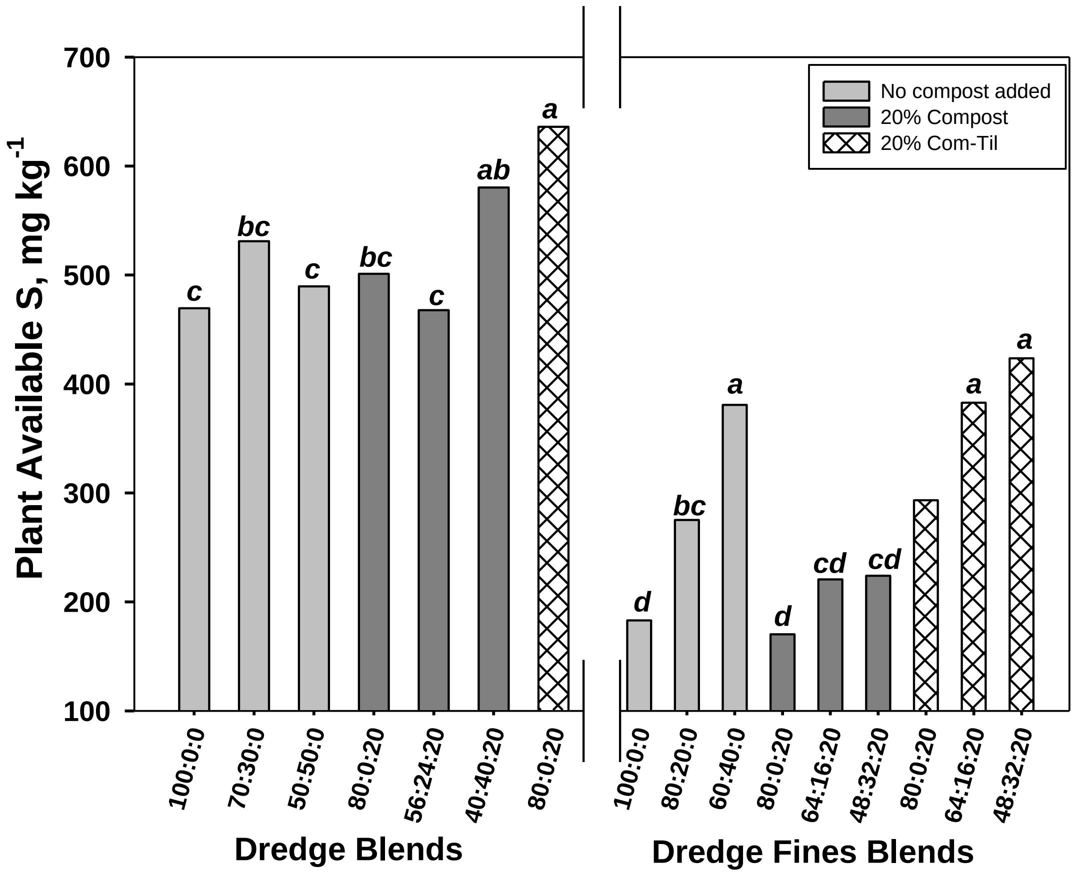


Fig. 43. Mean Plant Available Iron Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD (α = 0.05). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

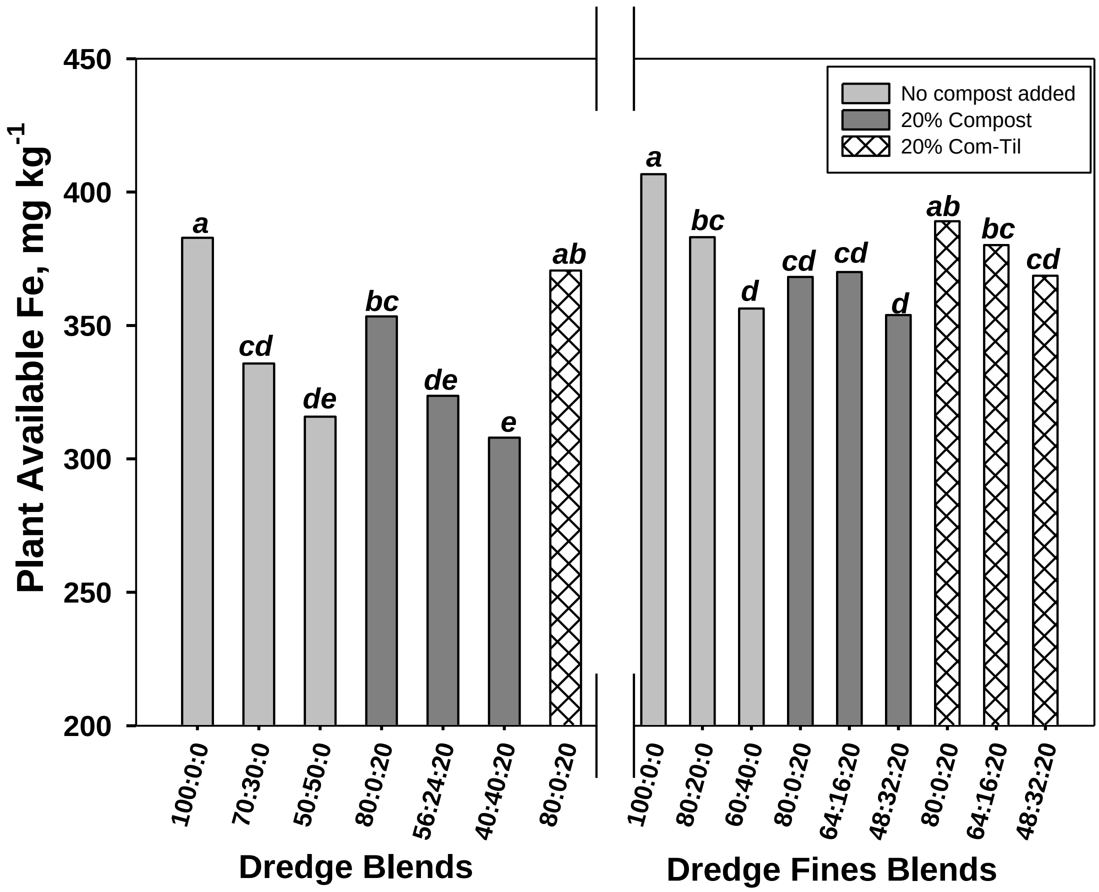


Fig. 44. Mean Plant Available Copper Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD ($\alpha = 0.05$). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

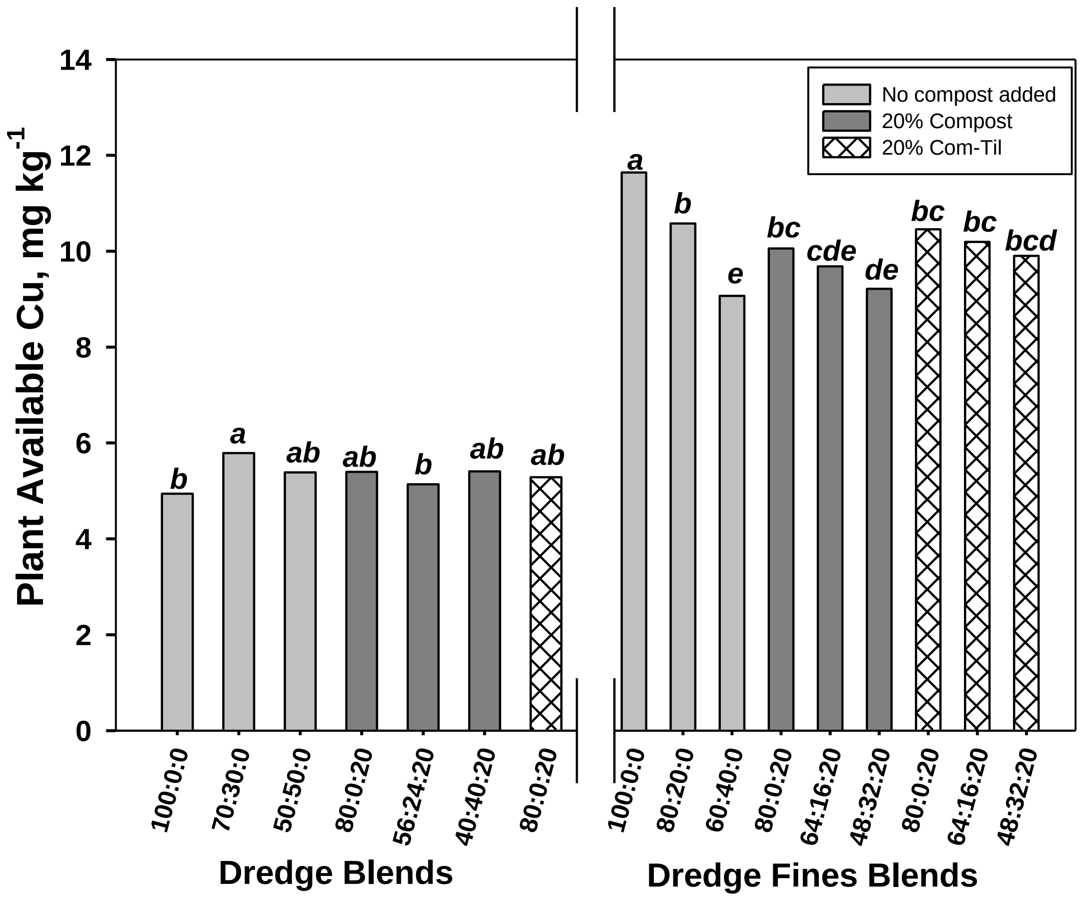


Fig. 45. Mean Plant Available Manganese Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD ($\alpha = 0.05$). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.

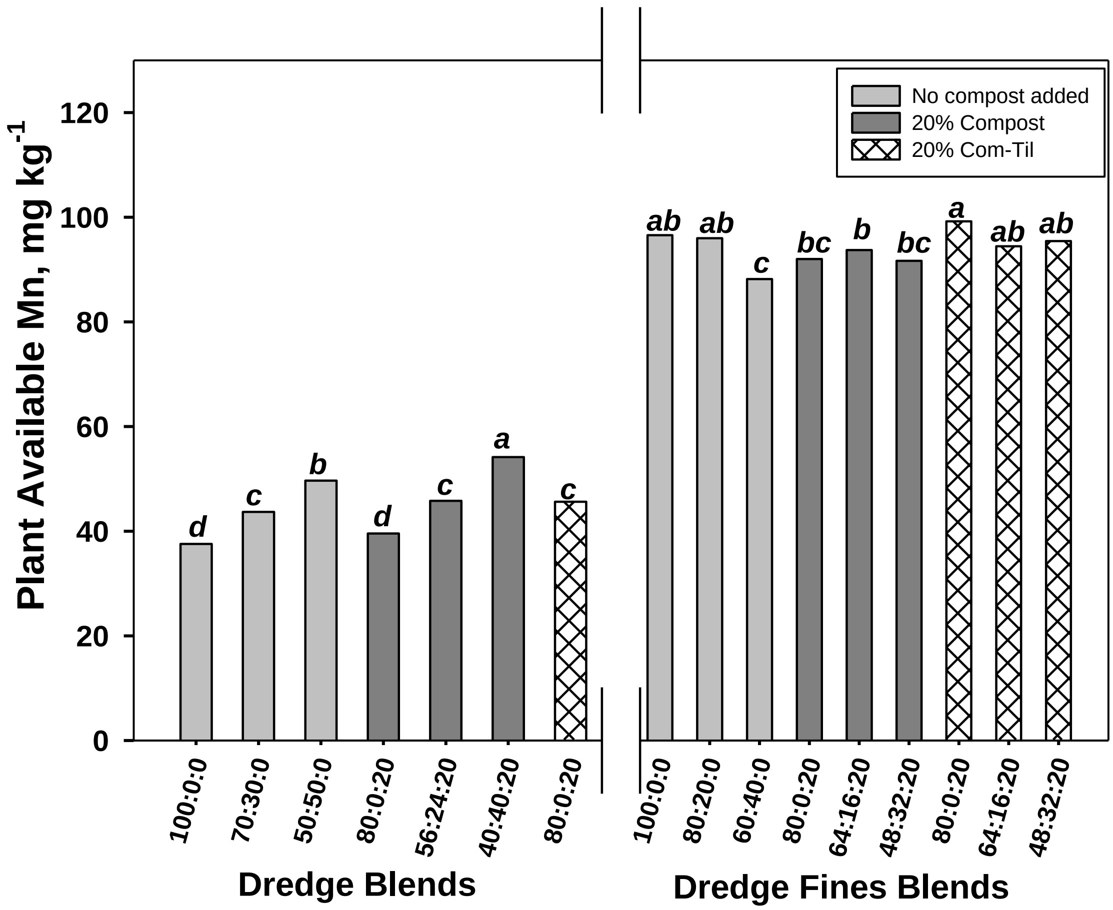
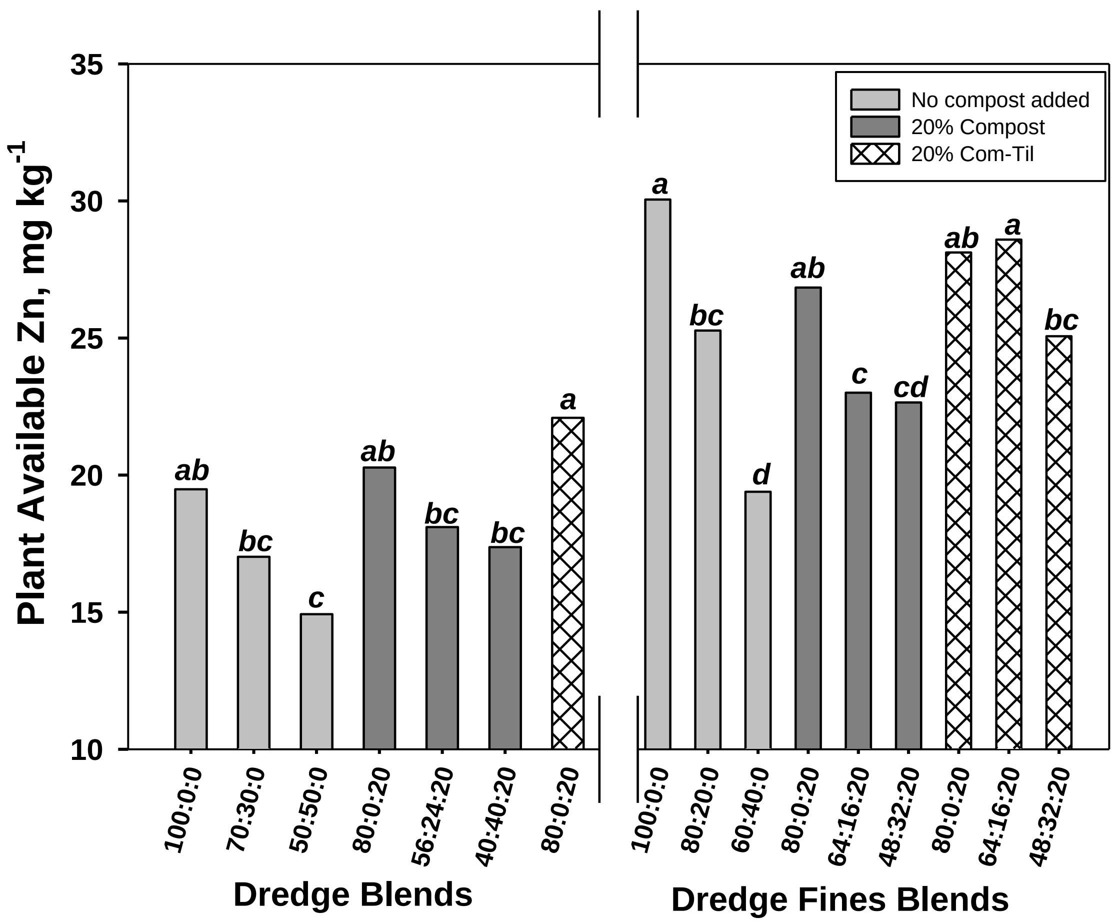


Fig. 46. Mean Plant Available Zinc Results for Dredge Blends and Dredge Fines Blends. Different letters represent significant difference between blend means using Tukey's HSD ($\alpha = 0.05$). Mean comparisons are made within but not between dredge materials as shown by break in x-axis.



References

Basta, N. T., Busalacchi, D. M., Hundal, L. S., Kumar, K., Dick, R. P., Lanno, R. P., … Granato, T. C. (2015). Restoring Ecosystem Function in Degraded Urban Soil Using Biosolids, Biosolids Blend, and Compost. *Journal of Environmental Quality*.

Basta, N. T., & Dayton, E. (2006). *Evaluating Steel Mill Sludges and Compost Blends: Ryegrass Growth and Blend Quality*.

Blake, G. R., & Hartage, K. H. (1986). Bulk Density. *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*, (9), 363–375.

Brady, N. C., & Weil, R. R. (1996). *The Nature and Property of Soils*. Upper Saddle River, NJ: Prentice-Hall Inc.

Bremner, J. M. (1996). Nitrogen-Total. In *Methods of Soil Analysis, Part 3. Chemical Methods* (pp. 1085–1121).

Brown, S., Mahoney, M., & Sprenger, M. (2014). A comparison of the ef fi cacy and ecosystem impact of residual-based and topsoil-based amendments for restoring historic mine tailings in the Tri-State mining district. *Science of the Total Environment*, *485-486*, 624–632.

Carlson, J., Saxena, J., Basta, N., Hundal, L., Busalacchi, D., & Dick, R. P. (2015). Application of organic amendments to restore degraded soil : effects on soil microbial properties. *Environmental Monitoring and Assessment*, *187*, 109.

Cassel, D. K., & Nielsen, D. R. (1986). Field Capacity and Available Water Capacity. *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods*, (9), 901–926.

Dane, J. H., & Hopmans, J. W. (2012). Water Retention and Storage. In *Methods of Soil Analysis: Part 4 Physical Methods* (pp. 688–690).

Daniels, W. L., Whittecar, G. R., & Iii, C. H. C. (2007). Conversion of Potomac River Dredge Sediments to Productive Agricultural Soils. In *National Meeting of Amer. Soc. of Surface Mining and Reclamation*.

Dayton, E., Basta, N., Whitacre, S., & McDonough, P. (2016). *Beneficial Reuse of Toledo Harbor Dredge Material in Manufactured Soil Blending: Performance and Economic/Logistical Considerations*.

Dayton, E. A., Whitacre, S. D., Dungan, R. S., & Basta, N. T. (2010). Characterization of Physical and Chemical Properties of Spent Foundry Sands Pertinent to Beneficial Use in Manufactured Soils. *Plant Soil*, (329), 27–33.

Decagon Devices Inc. (2014). Mini Disk Infiltrometer.

Doran, J. W., & Parkin, T. B. (1996). Quantitative indicators of soil quality: a minimum data set. *Soil Science Society of America Journal*, *49*, 25–37.

Elliott, H. A., O'Connor, G. A., Lu, P., & Brinton, S. (2001). Influence of Water Treatment Residuals on Phosphorus Solubility and Leaching. *Journal of Environmental Quality*, *31*(4), 1362–1369.

EPA, U. (2007). Method 6200 Field Portable X-Ray Fluorescence Spectrometry for the Determination of Elemental Concentrations in Soil and Sediment.

Franzluebbers, A. J., Haney, R. L., Hons, F. M., & Zuberer, D. A. (1995). Determination of Microbial Biomass and Nitrogen Mineralization following Rewetting of Dried Soil. *Soil Science Society of America Journal*, *60*(4), 1133–1139.

Gee, G. W., & Bauder, J. W. (1986). Particle-size Analysis·. In *Methods of Soil Analysis, Part 1. Physical and Mineralogical Methods* (2nd ed., Vol. 9, pp. 383–411).

Gugino, B. K., Idowu, O. J., Schindelbeck, R. R., Es, H. M. Van, Wolfe, D. W., Thies, J. E., & Abawi, G. S. (2009). *Cornell Soil Health Assessment Training Manual* (2.0 ed.).

Heanes, D. L. (1984). Determination of total organic - C in soils by an improved chromic acid digestion and spectrophotometric procedure. *Communications in Soil Science and Plant Analysis*, *15*(10), 1191–1213.

Idowu, O. J., Es, H. M. Van, Abawi, G. S., Wolfe, D. W., Ball, J. I., Gugino, B. K., … Bilgili, A. V. (2008). Farmer-oriented assessment of soil quality using field , laboratory , and VNIR spectroscopy methods. *Plant Soil*, *307*, 243–253.

Illinois Environmental Protection Agency. Title 35: Subtitle G: Chapter 1: Subchapter f: Part 742 Tiered Approach to Corrective Action Objectives (2013).

Johnson, G. V, Raun, R. R., Zhang, H., & Hattey, F. A. (2000). *Oklahoma State Fertility Handbook*. Divison of Agric. Sciences and Natrual Resources, Oklahoma State University, Stillwater, OK.

Lal, R., & Stewart, B. A. (1992). Need for Land Restoration. In *Advances in Soil Science* (Vol. 17, pp. 1–11).

Li, J., & Evanylo, G. K. (2012). The Effects of Long-term Application of Organic Amendments on Soil Organic Carbon Accumulation. *Soil Science Society of America Journal*, *77*, 964–973.

Logan, T. J. (1992). Reclamation of Chemically Degraded Soils. In *Advances in Soil Science* (Vol. 17, pp. 13–35).

Maynard, D. G., & Kalra, Y. P. (1993). Nitrogen and Exchangeable Ammonium Nitrogen. In *Soil Sampling and Methods of Analysis* (pp. 25–26).

Mehlich, A. (1985). Mehlich 3 soil test extractant : A modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis, 15*, 1409–1416.

Moebius, B. N., Es, H. M. Van, Schindelbeck, R. R., Idowu, O. J., Clune, D. J., & Thies, J. E. (2007). Evalution of Laboratory-Measured Soil Properties, *172*(11).

Nelson, D. W., & Sommers, L. E. (1996). Total Carbon , Organic Carbon , and Organic Matter. *Methods of Soil Analysis, Part 3. Chemical Methods*, (5), 961–1010.

Ogden, C. B., van Es, H. M., & Schindelbeck, R. R. (1996). Miniature Rain Simulator for Field Measurement of Soil Infiltration. *Soil Science Society of America Journal*, *61*(4), 1041–1043.

Ohio Environmental Council. (2013). Open Lake Disposal. Retrieved from http://www.ohioenvironmentalcouncil.org/publications/open-lake-disposal

Ohio EPA. (2015). Lake Erie Dredge Material Program. Retrieved from http://www.epa.ohio.gov/dir/dredge.aspx

Pierce, B. L., Redente, E. F., Barbarick, K. A., Brobst, R. B., & Hegeman, P. (1998). Plant Biomass and Elemental Changes in Shrubland Forages following Biosolids Application. *Journal of Environmental Quality*, *27*, 789–794.

Rhoades, J. D. (1996). Salinity : Electrical Conductivity and Total Dissolved Solids. *Methods of Soil Analysis, Part 3. Chemical Methods*, (5), 417–435.

Schindelbeck, R. R., Es, H. M. Van, Abawi, G. S., Wolfe, D. W., Whitlow, T. L., Gugino, B. K., … Moebius-clune, B. N. (2008). Comprehensive assessment of soil quality for landscape and urban management. *Landscape and Urban Planning*, *88*(2-4), 73–80.

Sharpley, A., Daniel, T. C., Sims, J. T., & Pote, D. H. (1996). Determining environmentally sound soil phosphorus levels. *Journal of Soil and Water Conservation*, *51*(2), 160–166.

Smith, P. K., Krohn, R. ., Hermanson, G. T., Mallia, A. K., Gartner, F. H., Provenzano, M. D., … Klenk, D. C. (1985). Measurement of Protein Using Bicinchoninic Acid. *Analytical Biochemistry*, *150*, 76–85.

Sumner, M. E., & Miller, W. P. (1996). Cation Exchange Capacity and Exchange. *Methods of Soil Analysis, Part 3. Chemical Methods*, *5*, 1201–1229.

Tsadilas, C. D., Mitsios, I. K., & Golia, E. (2005). Influence of Biosolids Application on Some Soil Physical Properties. *Communications in Soil Science and Plant Analysis*, *36*(4-6), 709–716.

Thomas, G. W. (1996). Soil pH and Soil Acidity. *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties*, (5), 475–490.

USDA NRCS. (n.d.). Saturated Hydraulic Conductivity. Retrieved February 22, 2017, from https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/office/ssr10/tr/?cid=nrcs144p2_074846

van Es, H. M., Schindelbeck, R. R., Melkonian, A., Moebius, B. N., & Idowu, O. J. (2006). Assessment of Soil Aggregate Stability using Small Rainfall Simulators. *Department of Crop and Soil Sciences Research Series*, *6*(1).

Weil, R. R., Islam, K. R., Stine, M. A., Gruver, J. B., & Samson-Liebig, S. E. (2003). Estimating Active Carbon for Soil Quality Assessment: A simplified method for laboratory and field use. *American Journal of Alternative Agriculture*, *18*(1), 3–17.

White, C. S., Loftin, S. R., & Aguilar, R. (1997). Application of Biosolids to Degraded Semiarid Rangeland: Nine-Year Responses. *Journal of Environmental Quality*, *26*, 1663–1671.

Wolf, J. M., Brown, A. H., & Goddard, D. R. (1952). An Improved Electrical Conductivity Method for Accurately Following Changes in the Respiratory Quotient of a Single Biological Sample. *Plant Physiology*, *71*(1), 70–80.

Wollum, A. G., & Gomez, J. E. (1970). A Conductivity Method for Measuring Microbially Evolved Carbon Dioxide. *Ecology*, *51*(1), 155–156.

Wright, S. F., & Upadhyaya, A. (1996). Extraction of an Abundant and Unusual Protein from Soil and Comparison with Hyphal Protein of Arbuscular Mycorrhizal Fungi. *Soil Science*, *161*(9), 575–586.

Zhang, R. (1997). Determination of Soil Sorptivity and Hydraulic Conductivity from the Disk Infiltrometer. *Soil Science Society of America Journal*, *61*, 1024–1030.

Zibilske, L. M. (1994). Carbon Mineralization. In *Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties* (pp. 835–863).