RESEARCH & DEVELOPMENT

Optimizing Compost Application Rates for Vegetation Health, Maximal Stormwater Infiltration, & Runoff Quality

Joshua L. Heitman, PhD
Richard A. McLaughlin, PhD
Christina N. Kranz, PhD
Crop and Soil Science Department
North Carolina State University

NCDOT Project 2019-06

FHWA/NC/2019-06

June 2022

Optimizing Compost Application Rates for Vegetation Health, Maximal Stormwater Infiltration, & Runoff Quality

North Carolina Department of Transportation
PROJECT AUTHORIZATION NO. RP 2019-06

Principal Investigators

Joshua L. Heitman, PhD
Professor

Richard A. McLaughlin, PhD
Professor

Christina N. Kranz, PhD
Postdoctoral Research Associate

Crop & Soil Sciences Department
North Carolina State University
Raleigh, North Carolina

Technical Report Documentation Page

1. Report No. Fill in number assigned by NCDOT, near end of project (e.g. FHWA/NC/2002-006)	2. Government Accession No. *Leave blank*	3. Recipient's Catalog No. *Leave blank*
4. Title and Subtitle Optimizing Compost Application Rates for Vegetation Health, Maximal Stormwater Infiltration, & Runoff Quality		5. Report Date June 2022 6. Performing Organization Code *Leave blank*
7. Author(s) Joshua L. Heitman, PhD Richard A. McLaughlin, PhD Christina N. Kranz, PhD		8. Performing Organization Report No. *Leave blank*
9. Performing Organization Name and Address North Carolina State University Department of Crop and Soil Science Campus Box 7620, Raleigh, NC 27695		10. Work Unit No. (TRAIS) *Leave blank* 11. Contract or Grant No. *Leave blank*
12. Sponsoring Agency Name and Address North Carolina Department of Transportation Research and Development Unit 104 Fayetteville Street Raleigh, North Carolina 27601		13. Type of Report and Period Covered Final Report August 1, 2018 – May 31, 2022 14. Sponsoring Agency Code 2017-45
Supplementary Notes: *Leave blank*		

16. Abstract\

Urbanization can degrade the natural function of soil through stripping of topsoil, vegetation removal, and compaction by heavy equipment. The result is an exposed, compacted subsoil with low fertility and infiltration, which leads to increased erosion and sediment loss, and impedes vegetation establishment. Strategic compost incorporation to disturbed, degraded urban soils may provide benefit to soil properties. Our research evaluated the effectiveness of different compost incorporation rates and compost sources as a stormwater control measures (SCMs). Two laboratory-scale experiments investigated the effect of compost incorporation rate on (1) saturated hydraulic conductivity (*Ks*) and (2) nutrient and heavy metal export patterns. First, results from the *Ks* experiments demonstrated that level of soil compaction (soil porosity) was a more important factor than compost rate for determining *Ks*. Compacted, low porosity soils with 50% compost by volume had significantly reduced *Ks* compared to medium and high porosity soils with no compost. Second, results from nutrient and heavy metal export experiments show stormwater largely did not increase the pollutant loads compared to DI water with compost incorporation. Compost rate does however influence pollutant transport and may retain most heavy metals when infiltrating stromwater. Next, a greenhouse experiment considered vegetation quantity with two sources of compost at varying rates. A compost application rate ≥10% by volume improved biomass production. Soil crusting was additionally mitigated in all compost treatments. Lastly, a field experiment determined the effects of compost incorporation on stormwater runoff volume, runoff quality (turbidity and total suspended solids [TSS]), infiltration rate (IR), bulk density, and vegetation establishment over the course of one year. Compost incorporation did not alter runoff quantity or quality compared to a tilled, no compost treatment. As compost rate was increased, bulk density decreased, vegetation biomass increased, and infiltration rates increased. More vegetation biomass was produced in the certified compost-amended treatments compared to treatments with the uncertified compost-amendment. Overall, the results of these studies suggest that the direct impact of tillage on soil properties is the primary factor affecting stormwater movement through soil. Compost incorporation has the greatest soil physical property improvement on heavier (more clay) soils and can improve vegetation establishment and growth, which is necessary for long-term erosion control. Tillage appears to be a viable option for reducing runoff volumes in compacted soils.

17. Key Words Infiltration rate, compost, tillage, runoff, vegetation, water retention, porosity	18. Distribution Statement *Leave blank*		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 46	22. Price *Leave blank*

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

DISCLAIMER

ACKNOWLEDGEMENTS

This work was supported by outstanding contributions from research support staff Adam Howard, Christopher Niewoehner, and Jamie Luther; professors Aziz Amoozegar, Amy Johnson, Grady Miller, and Erin Rivers; and many helpful undergraduate research assistants. We thank NCDOT staff for supporting all aspects of the project.

EXECUTIVE SUMMARY

Urbanization can degrade the natural function of soil through stripping of topsoil, vegetation removal, and compaction by heavy equipment. The result is an exposed, compacted subsoil with low fertility and infiltration, which leads to increased erosion and sediment loss, and impedes vegetation establishment. Strategic compost incorporation (tilling compost into the soil) to disturbed, degraded urban soils may provide benefit to soil properties. A progression of experiments were conducted to determine the optimal compost incorporation rates to improve stormwater infiltration, runoff quantity and quality, and vegetation establishment. Two laboratory-scale experiments investigated the effect of compost incorporation rate on (1) saturated hydraulic conductivity (*Ks*) and (2) nutrient and heavy metal export patterns. First, results from the *Ks* experiments demonstrated that level of soil compaction (soil porosity) was a more important factor than compost rate for determining *Ks*. Compacted, low porosity soils with 50% compost by volume had significantly reduced *Ks* compared to medium and high porosity soils with no compost. Second, results from nutrient and heavy metal export experiments show stormwater largely did not increase the pollutant loads compared to DI water with compost incorporation. Compost rate does however influence pollutant transport and may retain most heavy metals when infiltrating stormwater. Next, a greenhouse experiment considered vegetation quantity with two sources of compost at varying rates. There were no differences in the timeliness of vegetation germination between treatments. A compost application rate ≥10% by volume improved biomass production. Soil crusting was additionally mitigated in all compost treatments, while pure soil produced a soil crust, which is undesirable for long-term sediment and erosion control. Lastly, a field experiment determined the effects of compost incorporation on stormwater runoff volume, runoff quality (turbidity and total suspended solids [TSS]), infiltration rate (IR), bulk density, and vegetation establishment over the course of one year. Compost incorporation did not alter runoff quantity or quality compared to a tilled, no compost treatment. As compost rate was increased, bulk density decreased, vegetation biomass increased, and infiltration rates increased. More vegetation biomass was produced in the certified compost-amended treatments compared to treatments with the uncertified compost-amendment. Overall, the results of these studies suggest that the direct impact of tillage on soil properties is the primary factor affecting stormwater movement through soil. Compost incorporation has the greatest soil physical property improvement on heavier (higher clay content) soils and can improve vegetation establishment and growth, which is necessary for long-term erosion control. Tillage appears to be a viable option for reducing runoff volumes in compacted soils.

TABLE OF CONTENTS

List of Tables

List of Figures

INTRODUCTION

Soil erosion and stormwater runoff in urban areas are the biggest contributor to nonpoint source pollution according to the United States Environmental Protection Agency (USEPA, 2003). Soil loss rates from construction sites can be 10 to 20 times those of agricultural lands (USEPA, 2003). Urbanization can degrade the natural function of soil through vegetation removal, stripping of topsoil, and compaction by equipment. Development thus results in loss of soil organic matter (OM), increased bulk density, loss of soil structure, and reduced permeability.

Compost application to agricultural lands has been recognized as a reliable way to improve the physical properties of most soils, especially soils with poor structure and low levels of OM. There has also been a widespread interest in using compost to amend urban soils post-construction in order to improve soil function. Documented changes in physical properties in compost amended urban soils have included bulk density, infiltration rate, hydraulic conductivity, water content, aggregate stability, and porosity. These beneficial effects are interactive and are attributed to the compost materials applied and the amount of OM in the compost feedstock.

Previous research in North Carolina has demonstrated that tilling compost into the soil, or compost incorporation, can ameliorate compaction from construction activities (Alshraah, 2020; Mohommadshirazi et al., 2016, 2017). However, these studies included only one compost application rate and one compost source. Little research has been done to determine optimal compost application rates and source to concurrently improve stormwater infiltration, reduce sediment loss from site, and enhance vegetation establishment. Optimal compost rates are necessary to reduced costs associated with compost application and limit offsite release of pollutants. Too much compost or the wrong source of compost can inhibit vegetation establishment through nutrient immobilization.

The North Carolina Department of Environmental Quality (NCDEQ) recognizes soil improvements as a stormwater best management practice (BMP). It is important to optimize soil improvement specifications to ensure the most cost-effective solution is achieved. The North Carolina Department of Transportation (NCDOT) manages hundreds of miles land adjacent to roadways, much of it undergoing construction. Soil improvement BMPs can be applied to this land, and compost incorporation is appealing as a low-cost, low-impact solution to compaction and an alternative to built stormwater structures.

The studies included in this report were designed to determine the efficacy of compost additions to post-construction soils. First, we conducted two laboratory assessments to determine compost amendment rate effects on saturated hydraulic conductivity and water retention, and nutrient and heavy metal retention verses losses. Greenhouse tests of vegetation growth and establishment were used to evaluate the effects of compost on vegetation. Lastly, simulated post-construction soil conditions were used to examine the effects of compost rate on runoff quality and quality, infiltration rate, and vegetation establishment over one year at a field site in Raleigh, NC.

Results of Literature Review

An in-depth literature review supporting this work has been published in a refereed journal (Kranz et al., 2020). That publication is included in its entirety as Appendix 1; it provides additional details on specific studies and associated discussion.

Urban development can result in highly disturbed areas in which soil is severely compacted (Batey and McKenzie, 2006; Olson, et al., 2013). Soil can be compacted intentionally to increase soil strength or unintentionally from heavy equipment traffic. Topsoil is often removed during the construction process resulting in a nutrient poor subsoil exposed at the soil surface. Thus, development affects both soil physical properties and vegetation establishment (Crogger, 2005). Many studies have reported that compacted soils have reduced porosity (Crual, 1994; Schafer-Landfeld et al., 2004; Shestak and Busse, 2005), infiltration rate (Agassi et al., 1998; Crogger et al., 2008; Logsdon et al., 2017; Mohammadshirazi et al., 2017), and vegetation establishment (Mohammadshirazi et al., 2017; Evnylo et al., 2016; Alshraah, 2020), which, in turn, leads to increased runoff and erosion (Crogger, 2005; Violin et al., 2011). Runoff from compacted soils are often directed into overloaded stormwater systems and stream channels (Violin et al., 2011).

Establishing vegetation helps to create pathways in the soil for infiltration, which is necessary for erosion and sediment control (Bartens et al., 2011; Mohammadshirazi, et al., 2017). A method to improve the soil environment for vegetation establishment and for improved physical properties is to till or incorporate compost into the compacted subsoils. Incorporating compost can increase the porosity and infiltration rate, while compost additionally provides essential plant nutrients to the nutrient-depleted subsoil (Crogger, 2005). Compost can also remove pollutants from infiltrating stormwater, resulting in cleaner runoff (Hinman, 2009; Pitt et al., 1999). These beneficial effects are interactive and are attributed to the amount of compost applied and the amount of OM in the compost feedstock.

The hydrological response to compost incorporation in compacted soils has been variable, with compost incorporation increasing infiltration at some sites while tilling without adding compost was sufficient to improve infiltration at others (Logsdon, et al., 2017; Mohammadshirazi et al., 2016, 2017; Rivers et al., 2021). Logsdon et al. (2017) observed that compost incorporation improved infiltration compared to a no compost control and a compost blanket up to four years after compost application. Conversely, Mohammadshirazi et al. (2017) found that compost incorporation and tilling the soil resulted in the same infiltration two years after compost application. However, both compost incorporation and tilling increased infiltration compared to a compacted soil with no compost. Many studies on compost incorporation have only examined one compost application rate and one source of compost (Agassi et al., 1998; Crogger et al., 2008; Curtis and Claassen, 2009; Logsdon et al., 2017; Mohammadshirazi et al., 2016, 2017). The addition of compost to soils may have a range of effects on soil function due to the complexity of the soil's and compost's physical, chemical, and biological properties (Chahal et al., 2016; Curtis and Claassen, 2009).

Few studies have examined compost incorporation in the specific context of soil improvements for stormwater management. Limited information is available on the impacts of compost amendment rate on soil physical and hydrological properties (Crogger et al., 2008; Logsdon et al., 2017; Mohammadshirazi et al., 2016; 2017). Compost incorporation is recognized as a potentially beneficial practice for disturbed and degraded soils. However, the wide range of outcomes associated with compost application highlights the need for specific research on compost amendment rate and source as it related to stormwater management. *As the time of work summarized in this report, we are not aware of any studies that evaluated the effects of compost incorporation rate and source on soil physical and hydrological properties in post-construction soil.*

Report Organization

The main body of this report includes a summary of the methods and results for the laboratory, greenhouse, and field experiments. The first laboratory experiment involved three different soil textures and six different compost rates to evaluate the effect of compost amendment rate on saturated hydraulic conductivity and water retention. The second laboratory experiment measured nutrient and heavy metal retention of compost-soil blends. The greenhouse experiment compared vegetation establishment of compost-soil blends for two different sources of yard-waste compost. The field experiment involved comparison of tillage BMPs with different rates of compost and two sources of yard-waste compost. Runoff from natural rainfall events was measured for ten months at the site; infiltration rate and bulk density were also evaluated one year after plot establishment. Following the description of research activities, we include a summary of the main findings and associated recommendations.

In addition to these main sections of the report, we have included three appendices. The first appendix (as described above) is an extensive literature review on compost incorporation, published in a peer-reviewed journal. The second appendix is a peer-reviewed journal article (accepted pending minor revisions at time of writing this report) providing a more detailed report of the nutrient and heavy metal laboratory experiments. The third appendix is also a published peer-reviewed journal article providing a more extensive report from the field trials experiments on compost incorporation; herein we include only a summary of that work.

LABORATORY ASSESSMENT OF COMPOST AMENDMENT RATE ON HYDRAULIC PROPERTIES

The objective of this laboratory study was to determine the effects of compost amendment rate on saturated hydraulic conductivity (*Ks*) and water retention in order to identify target compost rates for enhancing soil infiltration. The research is summarized below.

Material and Methods

Three soil materials with different textures: (1) sandy loam, (2) silt loam, and (3) sandy clay loam and a commercial compost, McGill SportsTurf ®, were used to prepare soil-compost blends. The compost was a blend of woody materials, yard waste, agricultural by-products, and food waste. The compost provided by McGill is Seal of Testing Assured (STA) certified compost by the US Composting Council. Tests were conducted on soil alone and compost-soil blends with 10, 20, 30, 40, and 50% compost by volume. The test samples were packed in metal cylinders (7.62 cm × 7.72 cm [3 × 3 inch]) in one layer. All three soils and compost-soil blends were packed at a consistent 'medium' porosity of 0.5 m^3 m^{-3}. The sandy loam soil was also prepared at 0.55 (high) and 0.40 m^3 m^{-3} (low) porosity to evaluate different levels of compaction.

The K_S was measured using a combination of constant and falling head methods (Klute and Dickenson, 1986). Water retention was measured using a combination of a low-range and high-range pressure plate extraction (Klute, 1986). Pressure on the low-range plates were 25, 50, 100, 200, and 333 cm of water pressures. High-range pressure plate extraction was used for pressures of 1,020; 5,100; and 15,300 cm of water. An analysis of variance (ANOVA) was used to determine the variance in the measured *Ks* and water retention values ($p<0.05$). Individual differences between compost rates were analyzed using Tukey's HSD ($p<0.05$).

HYDRUS 1-D (Šimůnek et al., 2013) was used to simulate runoff and water movement through a simplified one-dimensional representation of a 100 cm (39 inch) drained sandy loam soil profile. Water movement was simulated using 1-hr design storm event from NOAA Atlas 14 (Bonnin et al., 2006). Design storm events at NC State University (Station ID 31-7079) with recurrence interval of 1-, 2-, and 5-year (equivalent to 3.48, 4.17, and 5.08 cm [1.37, 1.64, 2 inch] of rainfall, respectively) were retrieved from the U.S. National Weather Service Precipitation Frequency Data Server. The soil profile consisted of two soil layers: (1) a 15 cm (6 inch) amended layer, defined by the low, medium, or high porosity with 0 to 50% compost by volume from measured *Ks* and water retention values, and (2) a 85 cm (33 inch) highly compacted sub-surface layer defined by the low porosity, 0% compost *Ks* and water retention measured values.

Results and Discussion

Saturated Hydraulic Conductivity

The *Ks* of the treated soils are presented in Figure 1. There was a statistically significant compost treatment effect ($p<0.05$) and interaction between porosity and compost rate, and soil texture and compost rate ($p<0.05$). The *Ks* of the 50% compost application rate in the sandy loam soil was increased by 76.3% for the low porosity, by 24.5% for medium porosity, and by 27.1% for high porosity compared to the no compost control. Only the 50% compost application rate for the low porosity significantly increased *Ks* compared to the no compost control. For the medium porosity and high porosity groups, it took compost application rates of 40% and 20%, respectively, to increase *Ks* relative to the no compost control. A compost application rate of 20% significantly increased *Ks* for the sandy clay loam, while a 50% compost application rate significantly increased *Ks* for the silt loam from a no compost control. When comparing all three soil textures with a medium porosity, the sandy clay loam had higher *Ks* followed by the sandy loam and the silt loam, respectively.

As soil porosity increased, less compost was needed to significantly increase the *Ks* from the unamended control. This suggest that if a soil becomes compacted, even at high rates of compost, the benefit of compost for improving infiltration is lost. The importance of soil porosity is a critical finding for sites that receive little maintenance inputs, such as roadsides. It is important for these soils to infiltrate rainfall for the benefit of the vegetation planted in these areas and to reduce stormwater runoff volumes. The increase in *Ks* may improve the establishment and growth of plants as well as provide other ecosystem services such as reducing stormwater runoff and soil erosion in urban settings.

Water Retention

Water retention data were divided into three fractions: (1) drainable porosity or gravitational water, (2) plant-available water (PAW), and (3) unavailable water. Drainable porosity or gravitational water was defined as water draining from soil pores due to gravity (0 – 333 cm water tension). The PAW was defined as water that is available for plants to use (333 – 15,300 cm water tension). Unavailable water was defined as water that is tightly held, mostly being adsorbed by colloidal soil surfaces (> 15,300 cm water tension).

The sandy loam soil, high porosity treatment consistently had more drainable pore space (i.e., could not hold as much water against the force of gravity) than the low porosity treatments for all compost rates (Table 1, Figure 2). At compost application rates of 40% and 50%, there was significantly less drainable pore space in the high porosity treatments compared to the no compost control. There were no differences in the drainable porosity across compost rates for the low porosity treatment. Across porosities, the 40% and 50% compost application rate for the high porosity (sandy loam) treatment had the largest PAW values followed by the medium and low porosity treatments, respectively (Table 1, Figure 2). Conversely, the low porosity for 50% compost application rate had significantly less PAW than the unamended control. There were no differences in PAW across compost application rates for the medium porosity treatment. The high porosity treatment for all compost rates had reduced amounts of unavailable water compared to the low porosity. For all porosity treatments, there was a trend of higher compost application rates increasing water in the unavailable fraction.

The sandy clay loam and the silt loam soils had reduced gravitational water with increasing compost amendment rate (Table 2, Figure 3). There was no clear pattern to compost rate effects on drainable pore space in the sandy loam soil (Table 2, Figure 3). There were significantly higher PAW contents for the compost application rate of 40% and 50% than the unamended control in the sandy clay loam soil. For the silt loam soil, only a compost application rate of 30% was smaller than an unamended control. There were no differences across compost application rates for PAW in the sandy loam soil. With an increasing compost application rate, there was a trend of increasing water stored in the unavailable fraction for all soil textures compared to the unamended control. The silt loam, sandy clay loam, and sandy loam soils with a medium porosity had an increase of 149%, 79%, and 36% for water stored in the unavailable fraction with a 50% compost application, respectively. Differences in unavailable water fraction between textures were generally reduced with increasing compost rates.

When the soil was highly compacted, there was little difference in gravitational water content (i.e., drainable pore space) between compost rates since there was little pore space available. As the porosity increased (i.e., more void spaces), the drainable pore space increased at the same compost rate for the sandy loam soil. This suggests that if a goal of compost incorporation is to increase drainable pore space for stormwater management, then it is important to keep the high porosity of the soil-compost mixture. If the soil-compost mixture gets compacted, then drainable pore space will decrease, and the benefit of compost is lost.

Our results indicate that compost incorporation, even in sandy soils, may not alter PAW at high compost rates for some soil textures. Even the highest compost rates did not increase PAW in the silt loam and sandy loam (medium porosity) soils relative to the unamended control. However, the sandy clay loam and the high porosity sandy loam soils had a significant increase in PAW at 40% and 50% compost. Even though compost might not increase PAW per unit of soil volume, compost has been shown to increase the ability of roots to access available water by facilitating denser and deeper root growth.

HYDRUS 1-D Simulations

The low porosity treatment across all compost application rates had the largest amount of runoff for all design storm events and produced substantial runoff for all simulations at all compost rates (Figure 4). For the medium porosity soil, both the 1- and 2-year storm events produced runoff with 0%, 10%, 20%, and 30% compost application rates. All compost application rates, including the 40% and 50% compost, produced runoff with the 5-year storm event. The high porosity soil produced 0.2 cm (0.1 inch) of runoff with only 0% compost in the 1-year storm simulation. With a 2-year storm event, the high porosity 0%, 10%, and 20% compost application produced runoff at 1.0 cm (0.39 inch), 0.93 cm (0.37 inch), and 0.89 cm (0.35 inch), respectively. All compost application rates under high porosity produced runoff with the 5-year storm, but the amount was directly related to the compost rate.

For the 5-year storm, the high porosity 50% compost application rate reduced runoff 83.1%, while the 10% compost application reduced it 22.4% compared to the compacted control. Conversely, the low porosity soil, for all compost application rates, infiltrated very little water in each simulation, reducing runoff by less than 3%. This signifies that low porosity soils, even at high compost rates, are not suitable for stormwater management because they generate increased runoff compared to higher porosity soils.

Table 1. Average water retention grouped by gravitational, plant-available, and unavailable water at varying compost rates and porosities for the sandy loam soil. Lower case letters indicate significant differences by rows. Upper case letters indicate significant differences by column for each water retention fraction. ns = not significant. Tukey's HSD Test, $p<0.05$.

Compost (%)	**0**	**10**	**20**	**30**	**40**	**50**
Porosity†						
*Gravitational water (cm^3 cm^{-3})**						
Low	0.148 ns A	0.149 ns A	0.160 ns A	0.148 ns A	0.152 ns A	0.154 ns A
Medium	0.254 abc B	0.272 abc B	0.278 bc B	0.281 c B	0.247 ab B	0.245 a B
High	0.360 b C	0.332 b C	0.334 b C	0.341 b C	0.258 a B	0.246 a B
*Plant-available water (cm^3 cm^{-3})**						
Low	0.136 b NS	0.127 ab AB	0.119 ab AB	0.125 ab NS	0.133 b A	0.110 a A
Medium	0.133 ns NS	0.138 ns B	0.128 ns B	0.127 ns NS	0.153 ns A	0.126 ns A
High	0.117 a NS	0.120 a A	0.113 a A	0.107 a NS	0.186 b B	0.170 b B
*Unavailable water (cm^3 cm^{-3})**						
Low	0.114 a B	0.124 a C	0.139 b C	0.145 b B	0.137 b B	0.162 c C
Medium	0.107 ab B	0.103 a B	0.116 b B	0.117 b A	0.109 ab A	0.146 c B
High	0.087 a A	0.093 ab A	0.093 c A	0.109 c A	0.102 bc A	0.130 d A

* Gravitational water = 0-333 cm water. Plant-available water = 333-15,300 cm water. Unavailable water < 15,300 cm water.

† Low porosity = 0.40 m^3 m^{-3}, medium porosity = 0.50 m^3 m^{-3}, high porosity = 0.55 m^3 m^{-3}

Table 2. Average water retention grouped by gravitational, plant-available, and unavailable water at varying compost rates and soil textures. All porosities are medium (0.50 m^3 m^{-3}). Lower case letters indicate significant differences by rows. Upper case letters indicate significant differences by column for each water retention fraction. ns = not significant. Tukey's HSD Test, $p<0.05$.

Compost (%)	**0**	**10**	**20**	**30**	**40**	**50**
			*Gravitational water (cm^3 cm^{-3})**			
Sandy clay loam	0.327 e C	0.317 de C	0.303 cd C	0.289 bc B	0.272 b B	0.223 a B
Silt loam	0.223 bc A	0.246 d A	0.242 cd A	0.242 cd A	0.218 b A	0.146 a A
Sandy loam	0.254 abc B	0.272abc B	0.278 bc B	0.281 c B	0.247 ab B	0.245 a B
			*Plant-available water (cm^3 cm^{-3})**			
Sandy clay loam	0.072 a A	0.085 a A	0.080 a A	0.085 a A	0.130 b A	0.121 b A
Silt loam	0.188 b C	0.175 ab C	0.169 ab C	0.158 a C	0.178 ab C	0.186 b B
Sandy loam	0.133 ns B	0.138 ns B	0.128 ns B	0.127 ns B	0.153 ns B	0.126 ns A
			*Unavailable water (cm^3 cm^{-3})**			
Sandy clay loam	0.090 a B	0.095 a B	0.108 ab AB	0.121 b NS	0.102 ab A	0.161 c NS
Silt loam	0.068 a A	0.085 b A	0.098 bc A	0.112 cd NS	0.123 d B	0.169 e NS
Sandy loam	0.107 ab C	0.103 a C	0.116 b B	0.117 b NS	0.109 ab A	0.146 c NS

* Gravitational water = 0-333 cm water. Plant-available water = 333-15,300 cm water. Unavailable water < 15,300 cm water.

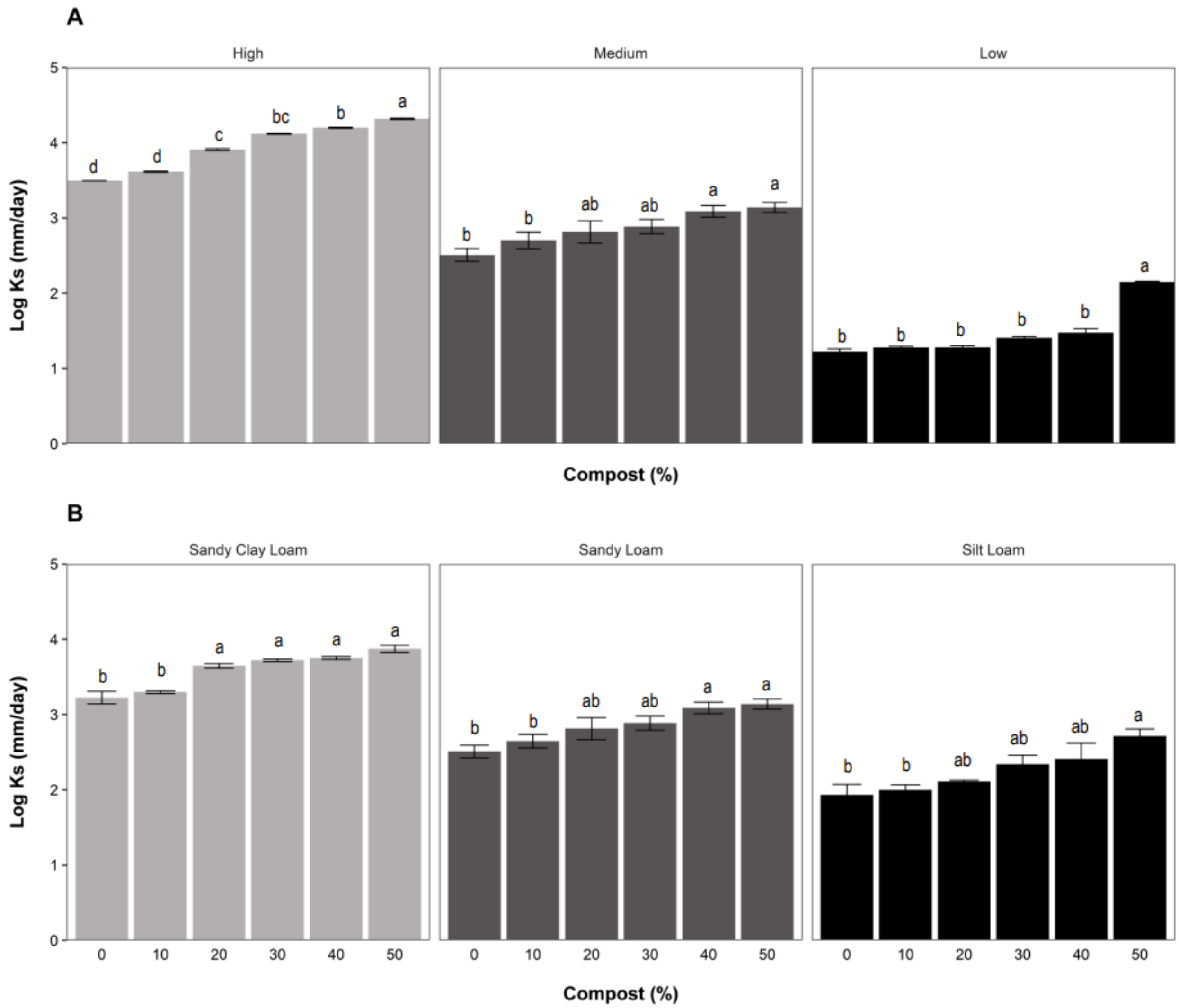


Figure 1. Saturated hydraulic conductivity (*Ks*) for varying compost rates for the (A) sandy loam soil grouped by porosity, and (B) medium porosity soil grouped by texture. Low porosity = 0.40 m^3 m^{-3}. Medium porosity = 0.50 m^3 m^{-3}. High porosity = 0.55 m^3 m^{-3}. Error bars ± 1SE, n=4. Letters indicate significant differences within each (A) porosity grouping and (B) soil texture (Tukey's HSD Test, $p<0.05$).

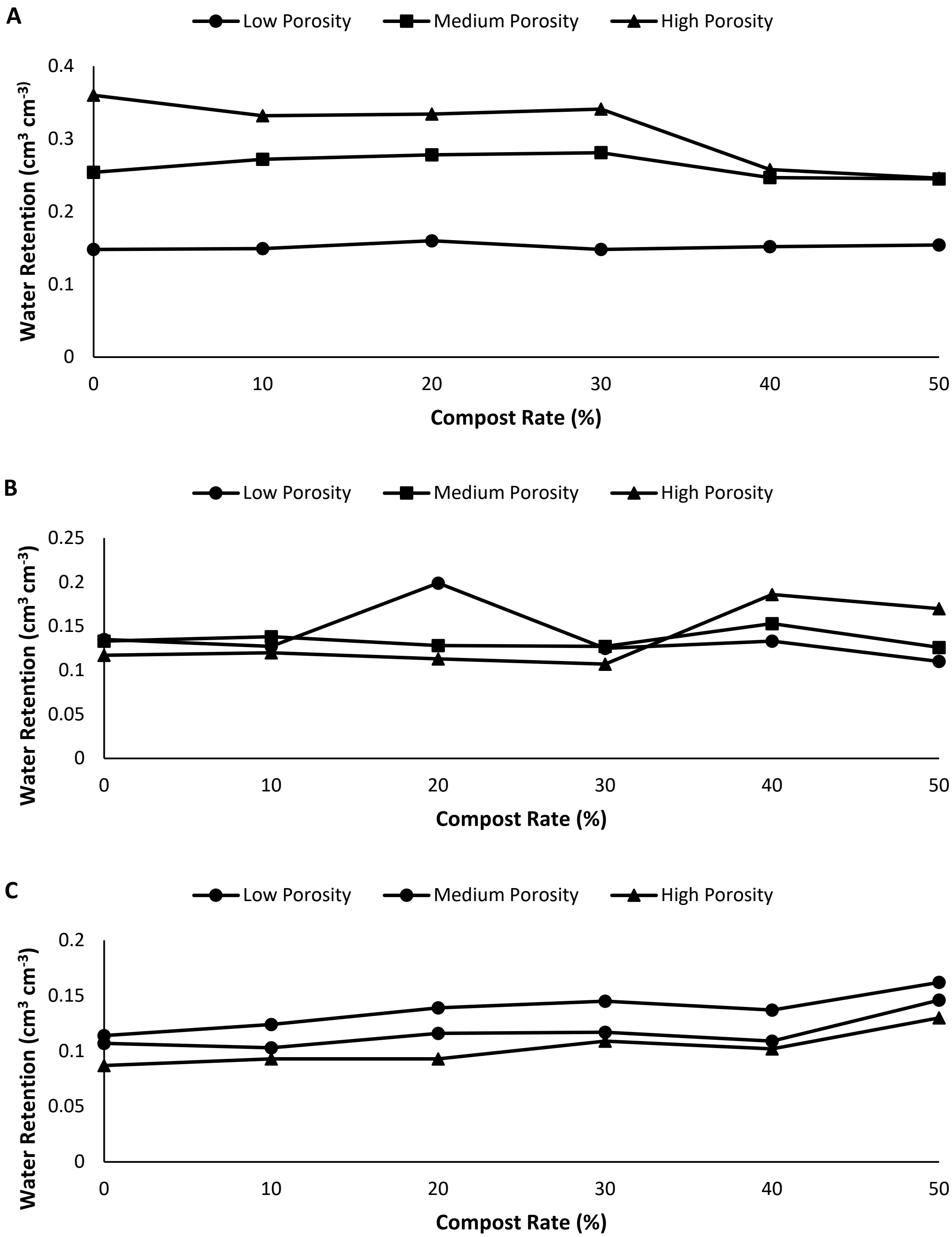


Figure 2. Average water retention grouped by (A) gravitational, (B) plant-available, and (C) unavailable water at varying compost rates and porosities for the sandy loam soil. Gravitational water = 0-333 cm water. Plant-available water = 333-15,300 cm water. Unavailable water < 15,300 cm water.

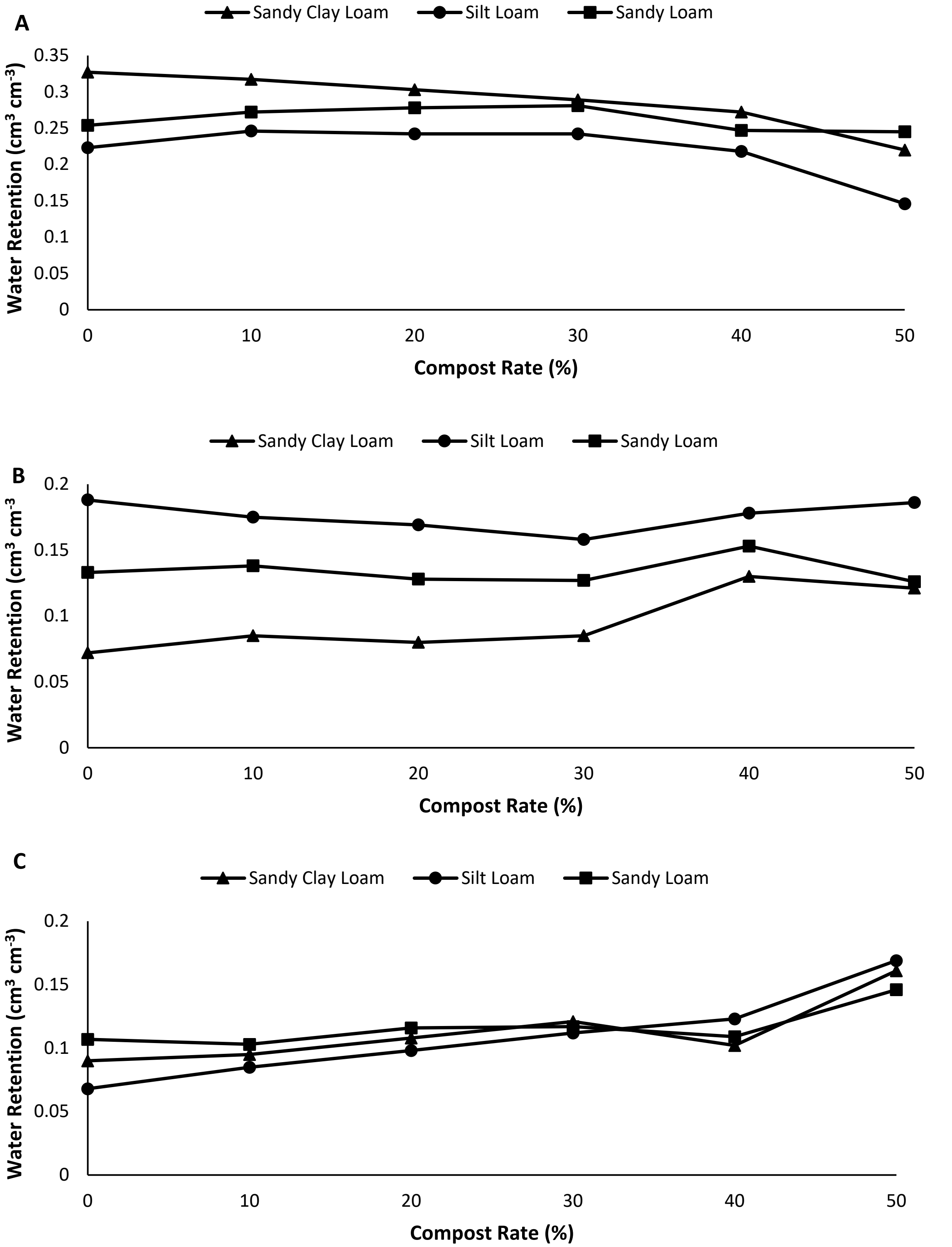


Figure 3. Average water retention grouped by (A) gravitational, (B) plant-available, and (C) unavailable water at varying compost rates and soil textures. Gravitational water = 0-333 cm water. Plant-available water = 333-15,300 cm water. Unavailable water < 15,300 cm water.

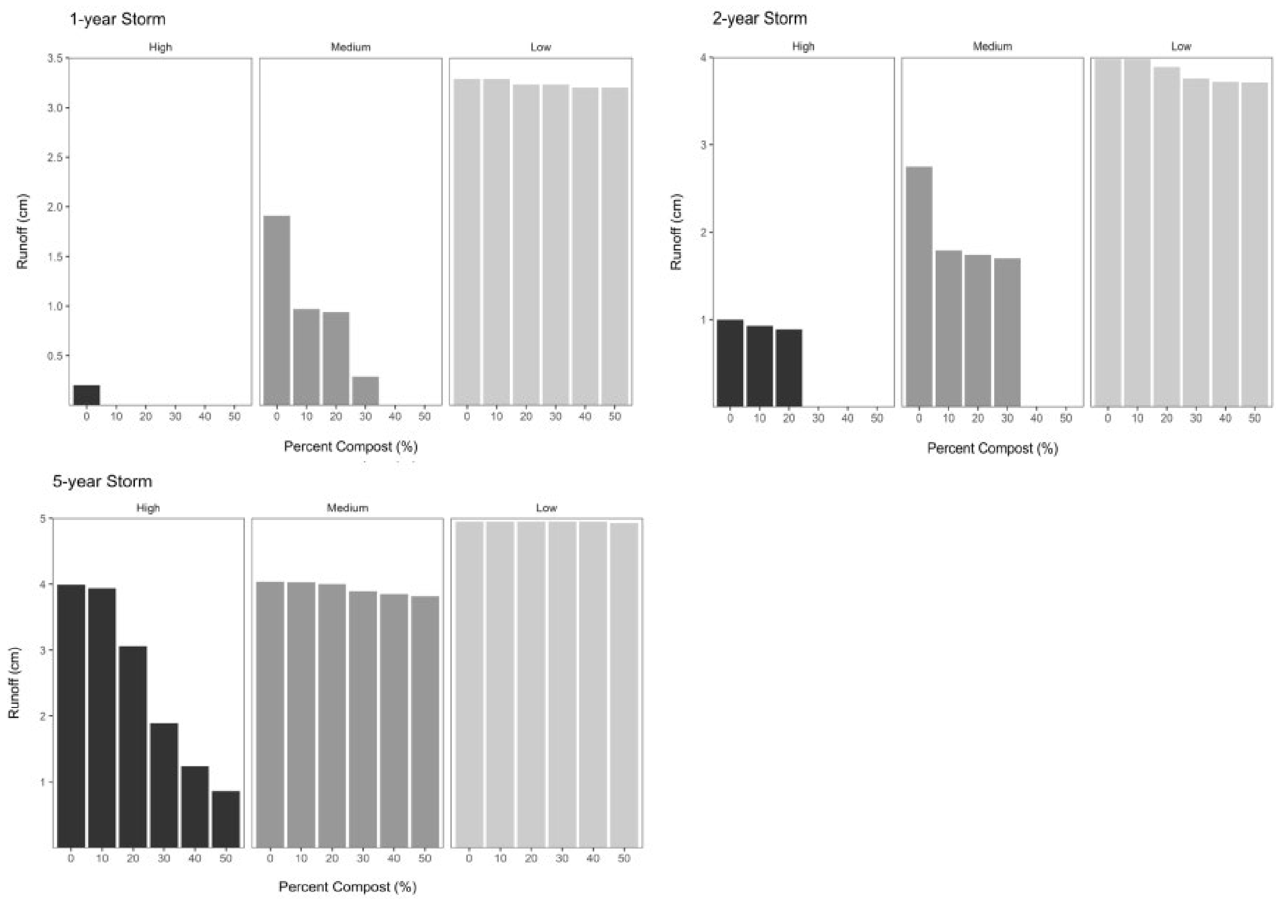


Figure 4. Total runoff across compost rates and porosities from HYDRUS-1D simulations using designed rainfall for the 1-, 2-, and 5-year storm return intervals for Raleigh, NC, USA. The porosity refers to the top 15 cm (6 inch) of the sandy loam soil profile, while the rest of the soil profile (85 cm, 33 inch) has a low porosity (highly compacted). Low porosity = 0.40 m^3 m^{-3}. Medium porosity = 0.50 m^3 m^{-3}. High porosity = 0.55 m^3 m^{-3}.

LABORATORY TESTING OF NUTRIENT AND HEAVY METAL LOSSES FROM COMPOST-SOIL BLENDS

The goal of study was to examine mobility and export patterns of nutrients and heavy metals of compost-soil blends through controlled laboratory experiments. Simulated stormwater (SW) and deionized water (DI) were used to leach columns containing soil, compost, and compost-soil blends. This allowed us to estimate the potential export of N, P, and heavy metals from compost=amended systems during stormwater infiltration. These data are currently under review for publication (pending minor revisions) in refereed literature. The manuscript draft is included in its entirety as Appendix 2, including additional details on methodology, results, and discussion. The research is summarized below.

Material and Methods

A sandy loam subsoil (73% sand, 16% silt, and 11% clay) and a yard-waste compost (McGill SportsTurf®) were used to produce compost-soil blends. Chemical analyses on the soil and compost are presented in Table 3.

Media used in this experiment were 0, 20, 50, and 100% compost by volume. All blends were mixed by hand on plastic sheets to obtain homogenous mixtures. A simulated stormwater solution was prepared as in Macnamara & Derry (2017) for metal concentrations and Subramaniam et al. (2015) for nutrient concentrations (Table 4). DI water was used as the base of the SW.

Flow rate was based on average draw down times for bioretention systems in North Carolina. The number of pore volumes leach through the columns was set based on the goal of supplying sufficient volume to capture the analyte export patterns, though this was not always achieved. Columns (15 cm [6 inch] tall and 8 cm [3 inch] diameter cylinders) were packed to a depth of 8 cm (3 inch) with the column media. The resulting treatment groups were deionized water (DI0, DI20, DI50, and DI100) and stormwater (SW0, SW20, SW50, and SW100) where the number refers to the percentage of compost.

All columns were pre-saturated with DI water for one hour prior to the commencement of the leaching period to normalize starting conditions. Half of the saturated columns were leached with DI water, and the other half were leached with SW, both using a Mariotte bottle (Figure 5) to reach a final flow-through volume equivalent to six times the porosity. All columns were leached at a rate of 1.75 mL min-1, equivalent to 1/10 pore volume of leachate collected every 10 minutes, for a total of 10 hours. Constant head and flow rate were maintained with a peristaltic pump (Figure 3). Six pore volumes of leachate were collected from each column in 1/10 fractions using a fraction collector. Samples were analyzed for dissolved nutrients (NH_4^+, NO_3^-, PO_4^{-3}) and heavy metals (Cd, Cr, Cu, Ni, Pb, Zn).

Export curves were generated for each analyte in the leachate collected for both DI and SW columns. The total export of each analyte was determined as the area under the export curve and was calculated using trapezoidal integration A factorial (2 x 4) ANOVA with least significant differences (LSD) was used to evaluate significant differences between treatments ($p<0.05$).

Table 3. Chemical analysis for sandy loam soil and McGill SportsTurf® compost.

Property	**Soil**	**Compost**
Carbon (%)	0.78	17.54
Nitrogen (%)	0.05	1.30
C/N Ratio	15.60	13.49
pH	4.70	7.00
Organic Matter (%)	1.65	20.74
Mehlich III Extractable P (mg kg^{-1})	11.00	254
Mehlich III Extractable Cu (mg kg^{-1})	0.82	0.46
Mehlich III Extractable Zn (mg kg^{-1})	1.41	18.64
NO_3-N (mg kg^{-1})	15.1	437
NH_4-N (mg kg^{-1})	9.40	3.50

Table 4. Simulated stormwater concentrations.

Constituent	**Source compound**	**Constituent concentration (mg L^{-1})**
Cd	Cadmium chloride	0.013
Cr	Potassium chromate	0.05
Cu	Copper sulphate	0.14
NH_4-N	Ammonium nitrate	1.55
Ni	Nickel nitrate	0.07
NO_3-N	Ammonium nitrate, nickel and lead nitrates	0.40
Pb	Lead nitrate	0.30
PO_4-P	Trisodium phosphate	3.26
Zn	Zinc chloride	0.69

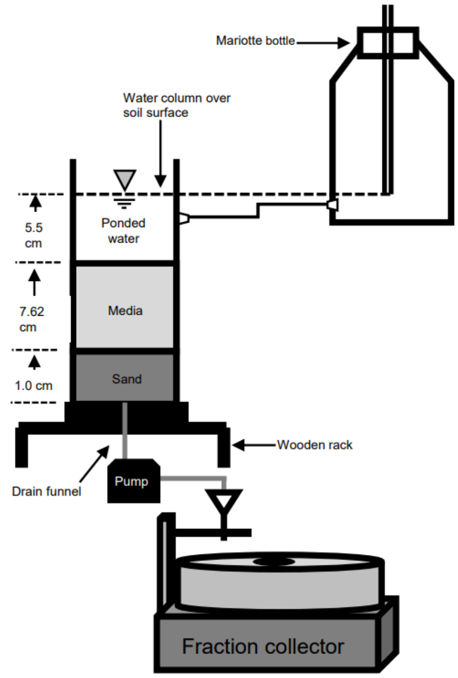


Figure 5. Schematic diagram of column experiment. The drawing is not to scale.

Results and Discussion

Ortho-phosphate

Export of PO_4^{-3} was significantly higher from 100% compost columns compared to the other treatments (Figures 6). The total export of SW100 (5.1 mg kg media^{-1}) was higher than that of DI100 (4.7 mg kg media^{-1}) ($p<0.05$, Figure 6). Total PO_4^{-3} export did not differ between leaching agents for other compost rates. Concentrations of PO_4^{-3} were highest with 100% compost likely because of high P content in the compost, which was 23× higher than in the soil (Table 3). The SW100 exported 17% of the PO_4^{-3} in the simulated stormwater solution, resulting in 83% retention (Figure 7). All other treatments retained more than 98% of the starting PO_4^{-3} concentration. When compost blends were leached with SW, the total PO_4^{3-} export did not increase relative to DI columns (Figure 6). This experiment demonstrated that compost blends have the ability to retain much of the PO_4^{3-} from SW. It is recommended to use a compost with ≤15% organic matter to reduce the chance of PO_4^{3-} leaching.

Ammonium

Export of NH_4^+ was highest from SW20 at 1.9 mg kg media^{-1} ($p<0.05$, Figure 6) and lowest from DI50 and SW50 at 0.1 mg kg media^{-1}. The soil used in this experiment had a higher concentration of NH_4^+ (9.40 mg kg^{-1}) compared to the compost (3.50 mg kg^{-1}), which could explain the differences in NH_4^+ export for the SW20. The labile NH_4^+ was flushed out of the soil within the first pore volume before declining to a steady concentration. The addition of SW produced a significant increase in export from the 20% compost blend, which exported the highest total amount of NH_4^+, or 44% of the added NH_4^+ (Figure 7).

Nitrate
Export of NO_3^- was highest from SW100 at 670 mg kg media^{-1} followed by the DI100 at 563 mg kg media^{-1} (Figure 6). Export was lowest from the soil-only columns at 7.0 mg kg media^{-1} (DI0) and 8.4 mg kg media^{-1} (SW0). In general, more NO_3^- was leached with increasing compost content and with SW. Nitrate was the only constituent that exported a higher rate than what was added from the SW (Figure 7). The 100%, 50%, 20%, and 0% compost exported 127×, 64×, 18×, and 2× more NO_3^- than was present in the SW, respectively. The pattern of increasing NO_3^- concentration and export as compost content increased can be attributed to the high amount of NO_3^- in the compost (437 mg kg^{-1}) compared to the sandy loam soil (15.1 mg kg^{-1}) (Table 3). The amount of NO_3^- leached from each treatment is likely reflective of the amount of NO_3^- in the treatment at the start of the experiment. This suggests that compost nitrate levels should be measured before choosing a source to use in stormwater practices.

Heavy Metals
Total export of all heavy metals was highest in SW100 (Figure 6). The total export of each heavy metal from the SW100 treatment was 7.8 µg Cd kg media^{-1}, 19.4 µg Cr kg-media^{-1}, 15.1 µg Cu kg media^{-1}, 16.0 µg Ni kg media^{-1}, 43.9 µg Pb kg media^{-1}, and 200 µg Zn kg media^{-1}. The total export of metals was similar between SW and DI columns from the 0%, 20%, or 50% compost treatments, except for Cd (Figure 6). In general, SW did not increase total export of metals. The total export of metals was significantly higher from the 100% compost columns, and the SW100 exported significantly more metals compared to the DI100, except for Cu (Figure 6). The compost treatments retained more than 70% of the original SW inputs (Figure 7). Metals showed similar patterns despite their differing chemical properties, suggesting that soil physical properties may play a critical role in regulating the distribution and mobility of these metals within the media.

Implications and Limitations
The column experiment suggests the labile fraction of pollutants may be flushed from the compost within several pore volumes, especially for low sorption affinity species. The observed decline in pollutants depended on the constituent; NH_4^+ and Cd were rapidly exported compared to the slower release of NO_3^- and Cu. These results suggest leaching potential of compost are the highest in the first few storm events, and the media may equilibrate over time. This study used one source of compost, and those with different characteristics may behave differently.

The column retention experiment constituted a short-term scenario amounting to an equivalent of 22.8 cm (9 inch) of cumulative rainfall. The average rainfall in North Carolina in 2018 was 174 cm (68 inch) (NOAA, 2019); thus, this experiment represents 13% of the annual rainfall. Essentially, this was a hurricane-like event as 22.8 cm (9 inch) rainfall moved through the system within 10 hours, a 1 in 500 year storm event (Bonnin et al., 2006).

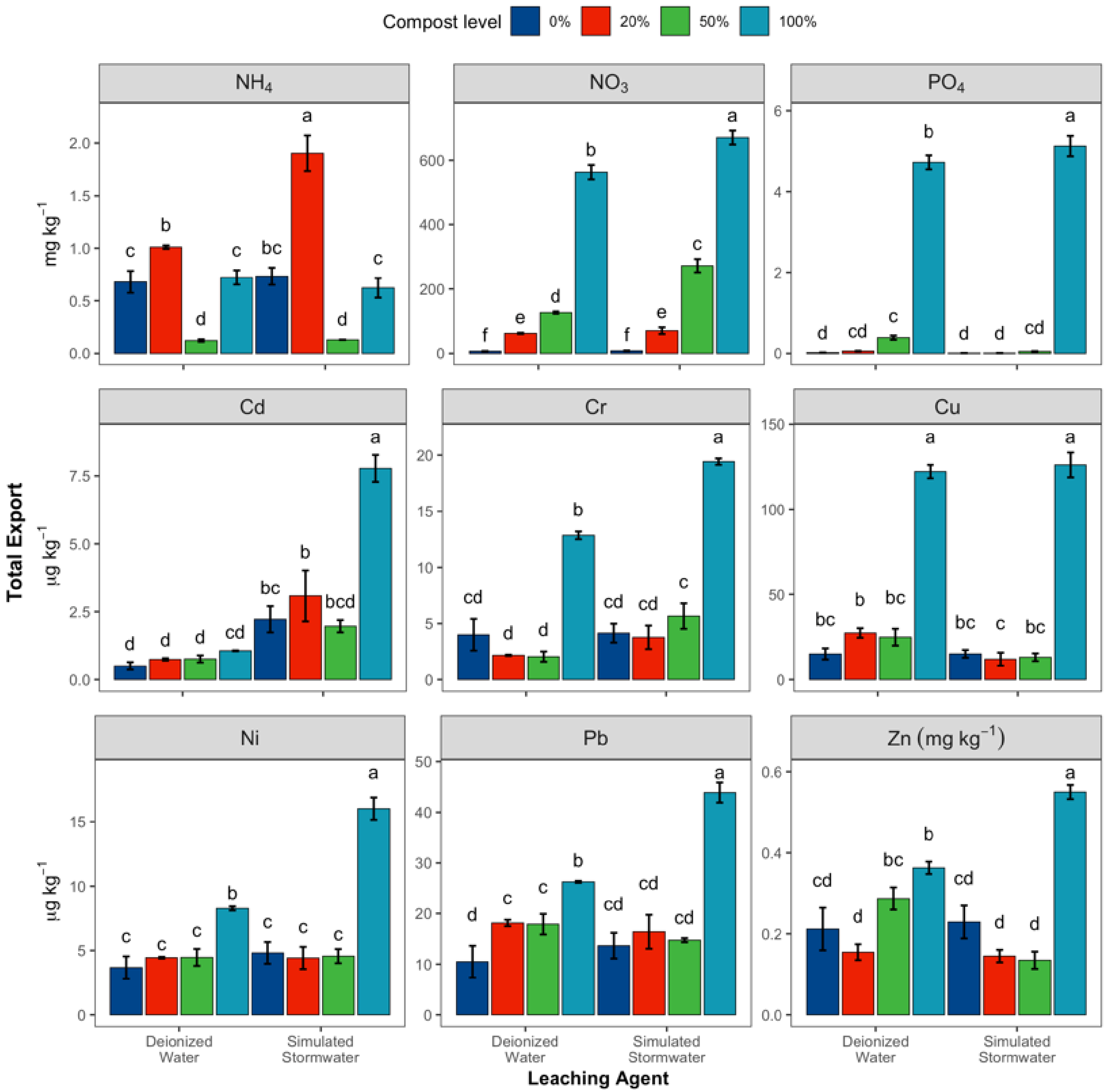


Figure 6. Total mass (±SE) of nutrients and heavy metals exported from experimental columns leached with deionized water and simulated stormwater. Letters indicate significant differences between treatments within each pollutant (LSD, $p < 0.05$).

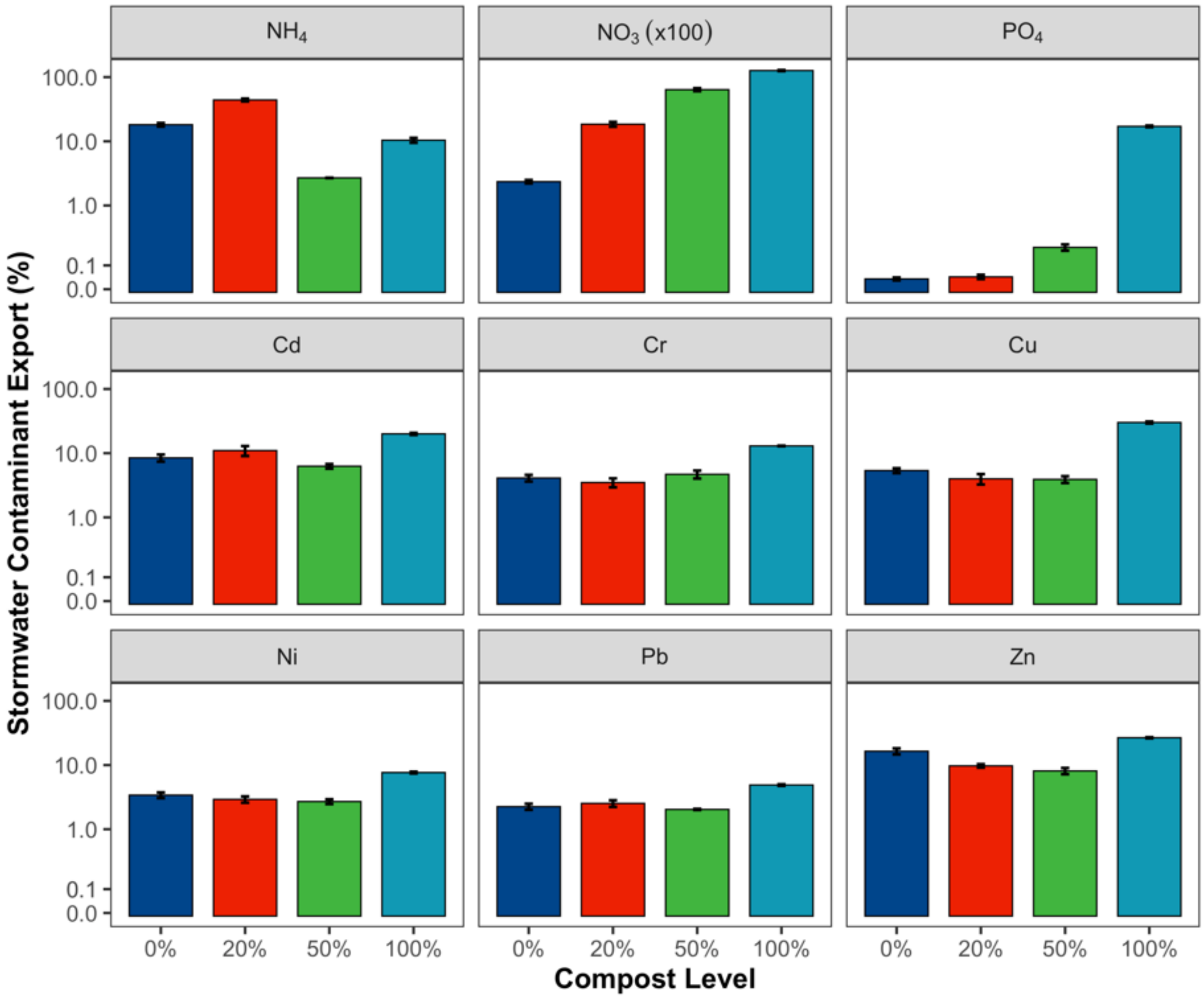


Figure 7. Export (±SE) of nutrients and heavy metals from experimental columns as a fraction of total added in simulated stormwater. The (×100) means the values should be multiplied by 100 to get the measured values. Values exceeding 100% (nitrate) indicate contributions from the matrix.

GREENHOUSE EVALUATION OF VEGETATION ESTABLISHMENT

The objective of this experiment was to understand how different sources of compost amendment and different rate of compost amendment effect turfgrass establishment, specifically the amount of biomass produced.

Material and Methods

Slotted flats with the dimensions of 25.4 x 52.1 x 6.35 cm (10 × 20.5 × 2.5 inch) for a total of 84.03 m^3 (42.71 ft^3). A sandy loam soil (73% sand, 16% silt, 11% clay) used in this experiment. The soil was blended with McGill SportsTurf® compost (certified) or North Carolina State University (uncertified) compost. The compost provided by McGill is Seal of Testing Assured (STA) certified by the U.S. Composting Council. The certified compost was a blend of green waste, food waste, biosolids, and woody materials. The uncertified compost was a blend of woody materials, yard waste, and food waste. A basic chemical analysis of the composts and soil is presented in Table 5.

Soil was mixed with either the certified or the uncertified compost at a rate of 0%, 10%, 30%, 50%, and 100% compost by volume. All flats received a 10-20-20 grade fertilizer at 560 kg ha^{-1} and pelletized dolomitic lime at 4483 kg ha^{-1} following NCDOT specifications (Table 6). Lights with an 11-hour photoperiod were used to aid in germination throughout the experiment. Flats were watered to field capacity daily for seven days before seeding. All flats were seeded on 03 December 2020 with a NCDOT seeding mix including tall fescue (*Festuca arundinacea*) at 84 kg ha^{-1} and hulled bermudagrass (*Cynodon dactylon*) at 28 kg ha^{-1}. Flats were watered to field capacity daily after seeding until the experiment concluded.

Aboveground biomass was harvested at the end of the experiment (week 5). All biomass was cut at the soil surface and placed into individual paper bags. Biomass was dried in an oven at 65°C for 48 hours or until constant mass was achieved for determination of dry mass. An ANOVA with least square difference (LSD) were applied at a level of 0.05 to compare differences between treatments.

Table 5. Chemical analysis for sandy loam soil and composts.

Property	Soil	Certified Compost	Uncertified Compost
Carbon (%)	0.78	16.6	41.42
Nitrogen (%)	0.05	1.45	1.64
C/N Ratio	15.60	11.44	25.26
pH	4.70	6.93	4.52
Organic Matter (%)	1.65	26.66	79.71
Mehlich III Extractable P (%)	0.001	0.32	0.19
Mehlich III Extractable Ca (%)	0.03	14.92	0.89
Mehlich III Extractable K (%)	0.006	0.37	0.48
Mehlich III Extractable Mg (%)	0.008	0.33	0.18
Mehlich III Extractable Na (%)	0.005	0.15	0.15
Mehlich III Extractable S (%)	0.001	0.23	0.14
NO_3-N (mg kg^{-1})	15.1	437	485
NH_4-N (mg kg^{-1})	9.4	3.5	287

Table 6. Greenhouse experimental setup specifications for treatments at Method Road Greenhouses, Raleigh, NC, USA.

Greenhouse Start	Compost	Compost Rate (%)*	Grass Seed Mixǂ	Fertilizer	Limestone
3 December 2020	McGill SportsTurf® (certified)	0, 10, 30, 50, 100	84 kg ha^{-1} Tall fescue, 28 kg ha^{-1} Hulled bermudagrass	560 kg ha^{-1}	4483 kg ha^{-1}
3 December 2020	NCSU€ (uncertified)	0, 10, 30, 50, 100	84 kg ha^{-1} Tall fescue, 28 kg ha^{-1} Hulled bermudagrass	560 kg ha^{-1}	4483 kg ha^{-1}

* Compost rate is percent by volume.
ǂ Common names listed in this table. Scientific names are provided in the text.
€ NCSU: North Carolina State University.

Results and Discussion

Compost Properties

The uncertified compost had 79.7% organic matter (OM) and 41.4% carbon (C), while the certified compost had 26.6% OM and 16.6% C (Table 5). The ideal range of OM in compost to aid in plant growth is 25-65% OM (USCC, 2001). The certified compost was within this range, but the uncertified compost was higher than the recommended amount of OM. Additionally, the C/N ratio of the uncertified compost (25.3) was considered high for vegetation establishment, while the certified compost (11.4) falls within the ideal C/N range (USCC, 2001). Well-composted materials reach a stable C/N ratio of 10 to 15, similar to the C/N ratio found in soil organic matter. The differences in feedstock materials may have led to the differences in OM, percent C, and C/N ratio. The percent N was comparable between the two sources of compost and falls within the ideal range for vegetation establishment (USCC, 2001). However, the uncertified compost had 82 times the amount of NH_4-N compared to the certified compost. High NH_4-N is an indication that the compost did not fully mature during the composting process.

Another major difference between the two sources of compost is the pH. The ideal pH range for compost is 6 to 7.5 (USCC, 2001). The certified compost pH falls within this range (pH 6.93), but the uncertifed compost's pH was too acidic at 4.5 (Table 5). An acidic compost can be a sign the compost did not fully stabilize or mature during the composting process. Additionally, the certified compost had 17 times the amount of calcium (Ca) compared to the uncertified compost. This could be a result of the compost feedstock having gypsum or lime included. Yet both the Ca levels fall within the acceptable range (USCC, 2001). All other nutrients analyzed fall within the acceptable range for vegetation establishment (USCC, 2001).

Biomass Production
The no compost control produced the least biomass (322 kg ha^{-1}), while the uncertified compost at 100% (1,169 kg ha^{-1}) and the certified compost at 100% (935 kg ha^{-1}) produced the most biomass. The 10%, 30%, and 50% compost rates for both sources of compost produced the same amount of biomass regardless of compost source (Figure 8, Table 7). The greater biomass produced by the 100% compost treatments was likely due to the supply of greater plant available N. In this short-term greenhouse experiment, it appears the two sources of compost, at the same application rate, led to the same amount of turfgrass biomass production despite having different nutrient profiles. There was also little differences in biomass production between the compost rates up to 50% compost by volume. It took a compost rate of 10% to produce more biomass than the control in a 5-week growing period.

Soil Crusting
The control treatment developed soil crusting during the experiment, but none of the compost treatments developed soil crusting (Figure 9). Compost is additionally known to stimulate the biological activity of degraded soils, which can make the soil more resistant to crusting. The stimulated biological activity along with increased turfgrass could be the reasons soil crusting was not observed in the compost treatments.

Table 7. Biomass (±SE) harvested five weeks after seeding. Experiment was conducted in a greenhouse. Letters indicate significant differences between treatments (LSD, $p < 0.05$).

Compost Source	Compost Rate (%)*	Biomass (kg ha^{-1})
No compost	0	322 ± 30 C
Certified	10	619 ±52 B
Certified	30	570 ± 45 B
Certified	50	649 ± 164 B
Certified	100	935 ± 145 A
Uncertified	10	549 ± 73 B
Uncertified	30	538 ± 124 B
Uncertified	50	676 ± 94 B
Uncertified	100	1169 ± 176 A

*Compost rate is percent by volume.

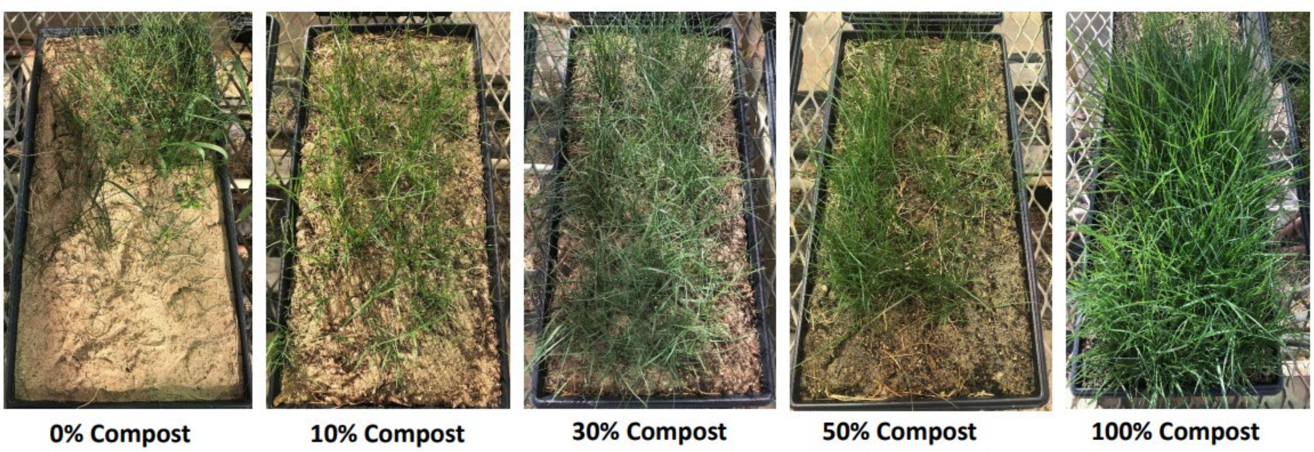


Figure 8. Week 5 of turfgrass growth before biomass sampling.

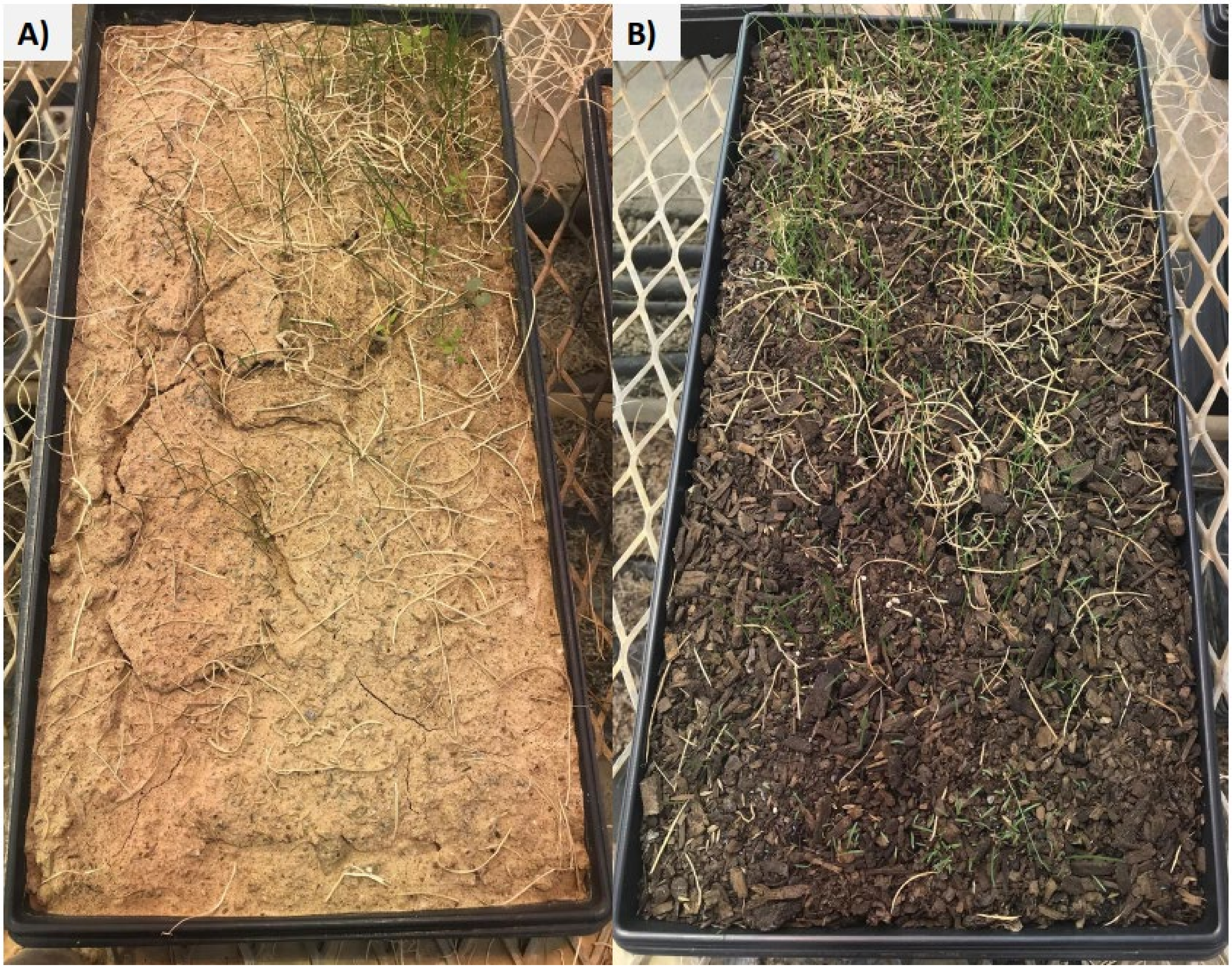


Figure 9. Week 2 of turfgrass growth for (A) the no compost control (100% sandy loam soil) with soil crusting and (B) the 100% uncertified compost without soil crusting. The excelsior blanket was removed for the photograph.

FIELD EVALUATION OF COMPOST-SOIL BLENDS FOR RUNOFF WATER QUANTITY AND QUALITY, INFILTRATION, AND VEGETATION ESTABLISHMENT

The purpose of this study was to determine the potential of compost incorporation to reduce runoff volume, improve runoff quality, and increase vegetation establishment at field scale over the course of a growing season. These data have been published in refereed literature (Kranz et al., 2022). The publication is included in its entirety as Appendix 2, including additional details on methodology, results, and discussion. The research is summarized below.

Material and Methods

The field study was conducted at the Lake Wheeler Road Field Laboratory, Raleigh, NC, USA, in the Piedmont region of North Carolina. The topsoil and vegetation were removed to expose the subsoil, and the area was graded to achieve a uniform surface with a slope of 5% to allow for some surface drainage. The subsoil was then tilled to approximately 15 cm (6 inch) depth. Each plot received fertilizer at a rate of 560 kg ha^{-1} and lime at a rate of 4483 kg ha^{-1}, according to NCDOT guidelines for grass establishment. Particle size analysis was performed on the exposed subsoil (0–15 cm depth (0-6 inch)). The subsoil contained 52% sand, 12% silt, and 36% clay (sandy clay texture).

Individual plots were delineated with wooden boards with an isosceles on the down slope end of the plot in order to funnel water to a collection point (Figure 8). A PVC pipe was attached between the two equal sides of the triangle to direct runoff to a 114 L plastic tub.

Compost was sourced from two manufactures: (1) McGill SportsTurf ® and (2) North Carolina State University. These compost sources were used to make compost-soil blends. The McGill compost was a blend of woody materials, yard waste, agricultural by-products, and food waste and is a Seal of Testing Assured (STA) certified compost by the US Composting Council. The North Carolina State University compost was a blend of woody materials, yard waste, and food waste and is uncertified. A basic nutrient analysis of the soil and compost is presented in Table 8.

Compost was tilled into the top 15 cm (6 inch) of the soil. The McGill compost (certified compost) was incorporated at 10% (C10), 30% (C30), and 50% (C50) compost by volume. The North Carolina State University compost (uncertified compost) was incorporated at 30% (U30) compost by volume. There was also a tilled only control (0% compost). All plots were seeded with a NCDOT seeding mix including tall fescue (*Festuca arundinacea*) at 84 kg ha^{-1} and hulled bermudagrass (*Cynodon dactylon*) at 28 kg ha^{-1}. Excelsior matting was used to cover the plots after seeding and anchored with metal sod staples (Figure 9).

After each natural rain event, the runoff volumes were determined by depth of water in the collection tank. Water from each tub was then samples for total suspended solids (TSS) and turbidity. Grass biomass samples were collected after each mowing. Clippings were cut to 10 cm (4 inch) above the ground in accordance with NCDOT mowing guidelines. Samples were placed in paper bags, dried at 65 °C for 48 h, and then weighed to determine above ground biomass.

Bulk density and infiltration rate (IR) measurements were taken 11 months after plot establishment in April 2021. Bulk density samples from the upper 10 cm (4 inch) of the soil were taken using a 6 cm (2.4 inch) diameter core sampler. Bulk density samples were oven dried at 105 °C and reweighed to determine the water content and bulk density. The constant head single-ring infiltrometer method was used to measure IR. The IR was calculated from these data using the Reynolds and Elrick (1990) method. A one-way ANOVA with Tukey's HSD pairwise comparison (α = 0.05) was used to evaluate differences between treatments for biomass, runoff, IR, bulk density, water content, TSS, and turbidity.

Table 8. Nutrient analysis of composts and soil.

Property	Certified Compost	Uncertified Compost	Subsoil
Organic Matter (%)	26.7	79.7	1.6
Carbon (%)	17.7	30.4	0.7
Total Nitrogen (%)	1.45	1.64	0.06
C/N Ratio	12.2	18.5	11.7
Total Phosphorus (%)	0.32	0.19	0.07
Total Potassium (%)	0.37	0.48	0.16
pH	6.7	6.3	4.4

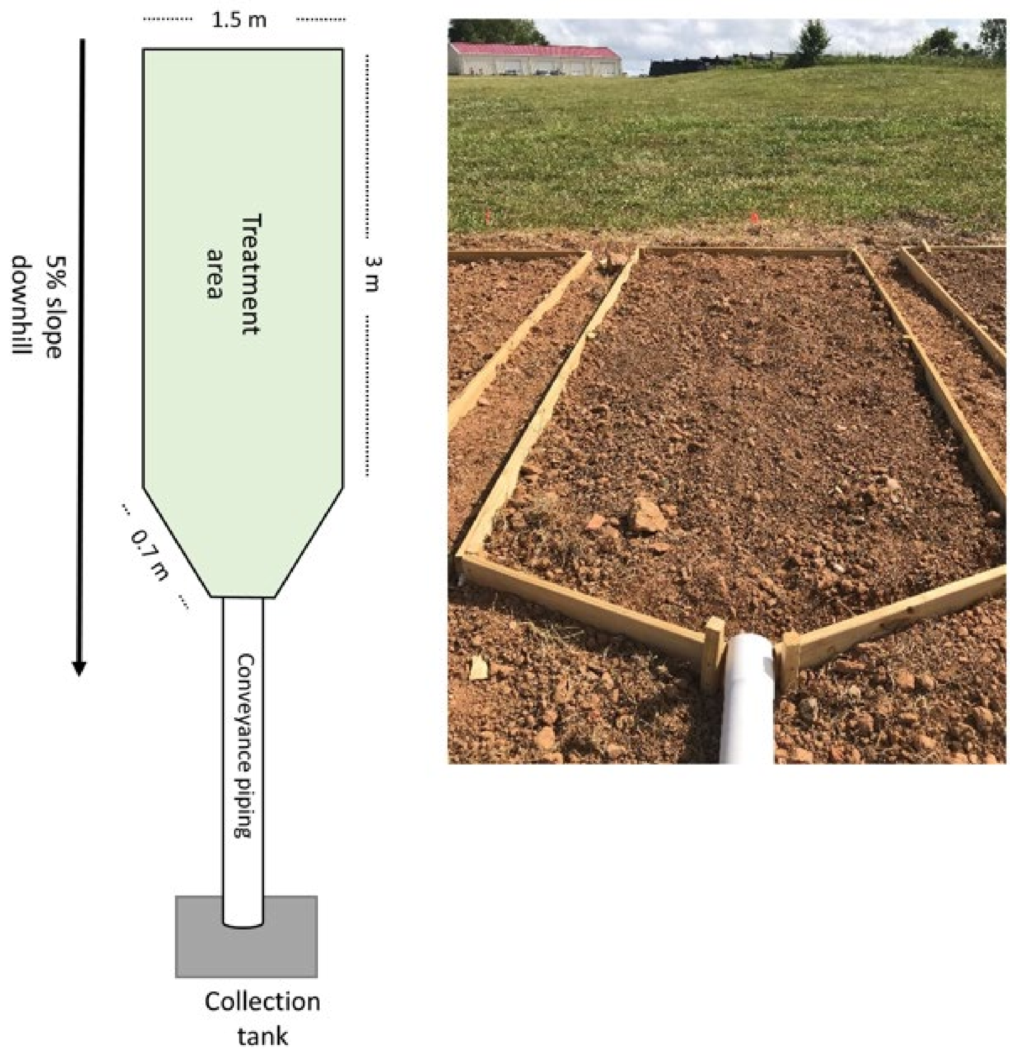


Figure 10. (Left) Top view of site configuration showing connection between plot area and collection tank; (Right) Plan view of site configuration before treatment application looking upslope.

Figure 11. Site preparation evolution.

Results and Discussion

Runoff Quantity and Quality

Mean rainfall per storm event during the collection period was 57 mm (2.2 inch), and mean rainfall intensity per storm event was 55 mm h^{-1} (2.1 inch h^{-1}). There were no differences between treatments for each individual storm event (Figure 10). In all cases, runoff volume was less than 10% of total rainfall across the full length of the study. The soil texture at this site is a sandy clay with 52% sand. Tilling alone was enough to loosen the soil in order to achieve high infiltration rates for this sandy soil.

There were no differences in turbidity, with an average value of 21 NTU (Figure 11). The average turbidity from this experiment (21 NTU) was also below the North Carolina Department of Environmental Quality (NCDEQ) surface water quality standards for aquatic life and secondary recreation for both freshwater (<50 NTU) and saltwater (<25 NTU). However, the average turbidity reported here would be unsuitable for sensitive water bodies such as trout streams (<10 NTU).

For TSS, one storm event, 7 July, resulted in significant differences, while no differences were found on any other storm dates (Figure 11). The U30 runoff resulted in higher TSS compared to the control, but the U30 was not different from the certified compost treatments. In this study, the use of compost, up to 50% by volume, did not increase nor decrease the turbidity or TSS in runoff compared to the control.

Vegetation Establishment
Biomass was collected four times during the field study and added together to get cumulative biomass produced in one growing season. The C50 treatment generated more biomass followed by the C30, C10, control, and U30 treatments, respectively (Table 9). The certified compost resulted in greater biomass production compared to the uncertified compost. The C50 treatment produced more than double the biomass compared to the control and U30. The certified compost also led to increased biomass with increased rates of compost. The uncertified compost had higher levels of organic matter (79.7%) and carbon (30.4%), which led to a C/N ratio of 18.5, compared to the C/N ratio of 12.2 from the certified compost (Table 8). Higher C/N ratios are known to immobilize nitrogen, which can inhibit vegetation growth.

Bulk Density and Infiltration Rate
The control treatment resulted in lower water content and increased bulk density compared to the compost incorporated treatments (Table 9). There were no differences in water content between compost treatments. The C50 treatment resulted in the lowest bulk density at 0.88 g cm^{-3}, followed by the C30 (0.96 g cm^{-3}), U30 (1.03 g cm^{-3}), C10 (1.19 g cm^{-3}), and the control (1.35 g cm^{-3}). With each increase in compost application rate, there was a decrease in the bulk density.

Compost incorporation significantly improved the IR to 36.0 to 67.9 cm h^{-1} compared to the tilled only control at 27.3 cm h^{-1} (Table 9). Mean rainfall and storm intensity from the 20 storm events were 5.66 cm and 5.47 cm h^{-1}, respectively, and these values are smaller than the measured IR. This demonstrates while, while there are differences in IR between treatments, the rainfall and storm intensity were too small to capture the differences between treatments using observed runoff from natural events. The U30 and C50 treatments resulted in the same IR. The uncertified compost resembled a mulch with large pieces of woody debris present, while the certified compost was screened for finer particle size. The differences in particle sizes within the compost between the two sources could have cause the observed differences in IR.

Table 9. Total biomass for all four sample dates (± 1SE), n=16, and water content (± 1SE), bulk density (± 1SE), and infiltration rate (IR) (± 1 SE) of treatment plots 11 months after establishment, n=8. Letters indicate significant differences between treatments (Tukey's HSD Test, $p<0.05$).

Treatment	**Total Biomass (kg ha^{-1})**	**Water Content (%)**	**Bulk Density (g cm^{-3})**	**IR (cm h^{-1})**
Control	20,241 (247) d	10.2 (0.3) b	1.35 (0.03) a	27.3 (4.2) c
C10	37,522 (507) c	16.0 (3.8) a	1.19 (0.04) b	36.0 (2.7) b
U30	19,175 (284) d	16.3 (0.9) a	1.03 (0.04) c	67.9 (13.5) a
C30	46,044 (415) b	18.8 (0.7) a	0.96 (0.03) c	40.9 (4.7) b
C50	49,370 (545) a	21.2 (1.0) a	0.88 (0.03) d	64.1 (8.4) a

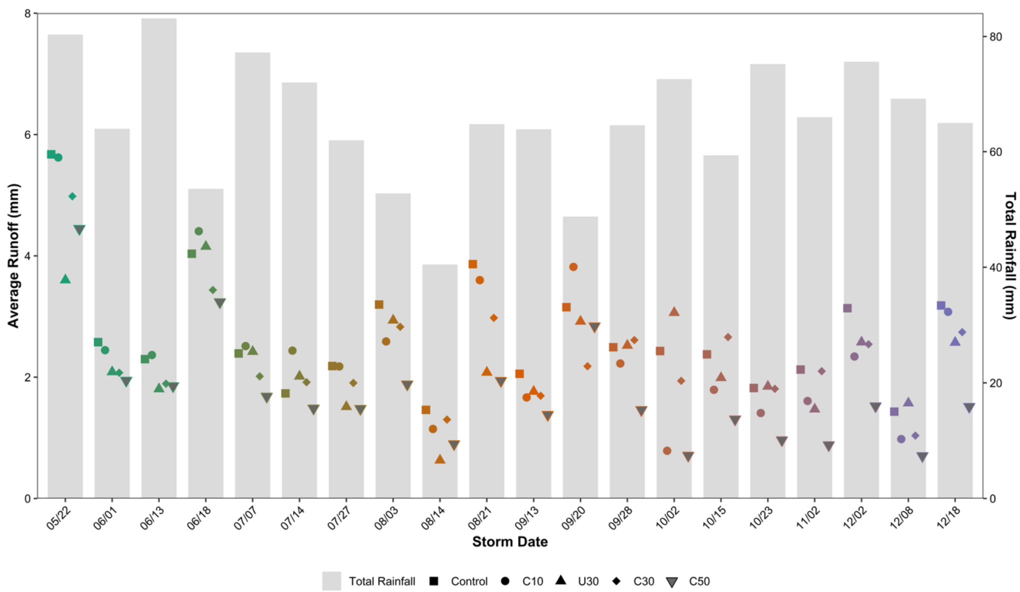


Figure 12. The symbols indicate the average runoff for each treatment from storm dates (mm/dd). The grey bars indicate the rainfall that occurred from each storm. Control: no compost. C10: 10% certified compost. U30: 30% uncertified compost. C30: 30% certified compost. C50: 50% certified compost.

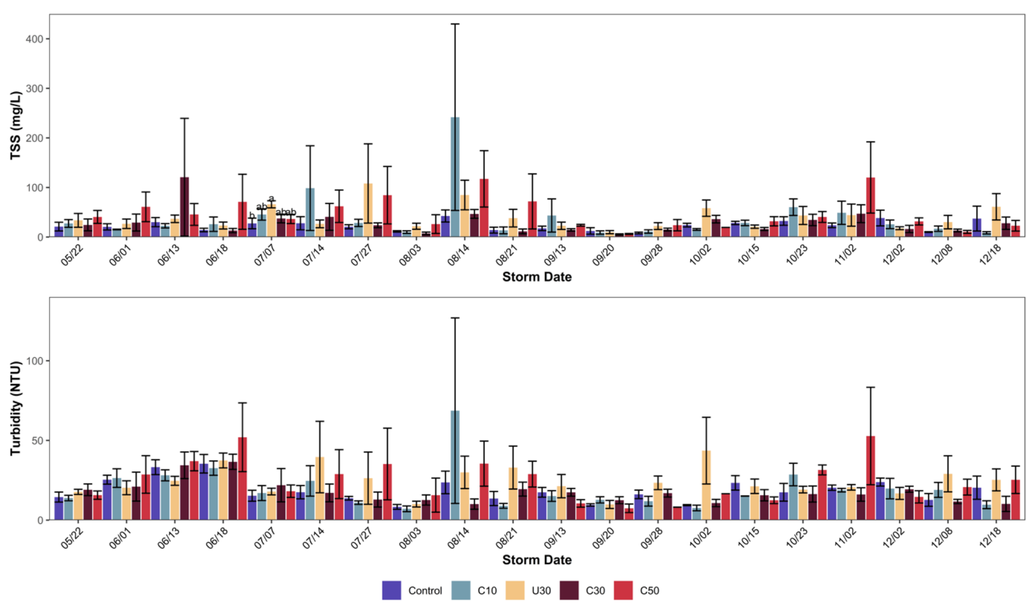


Figure 13. (Top)Total suspended solids (TSS); (Bottom) Turbidity from runoff samples by storm date (mm/dd). Error bars ± 1SE, n=4. Letters indicate significant differences between treatments by date (Tukey's HSD Test, p<0.05).

FINDINGS AND CONCLUSIONS

Construction activities can severely affect soil physical and hydrological properties, which leads to reduced stormwater infiltration, poor vegetation establishment, and increased erosion. Prior research in North Carolina has shown that tilling the soil is an effective way to loosen the soil in order to increase infiltration rate, improve vegetation establishment, and reduce bulk density. Additional research has demonstrated the benefits of compost incorporation for resisting compaction from mower traffic up to 2 years after compost application.

In this study, higher rates of compost tended to improve soil physical properties and generate more vegetation biomass compared to lower rates and no compost treatments. In examining the effects of compost on soil hydraulic properties in our initial laboratory measurements, the soil porosity (compaction level) played an important role in determining the infiltration rate. However, the benefits of compost were lost when the soil became compacted, even at the highest (50% by volume) compost application rate. The amount of compost needed to achieve improvements in infiltration was also related to soil texture. Sandy textured soils with low clay content need less compost to achieve overall improvements in hydrologic function, and these compost additions to sandy soils increased moisture retention, which could aid in vegetation establishment.

Using compost as a stormwater control measure poses a potential concern for runoff quality and the timeliness of vegetation establishment. Results from our laboratory testing of nutrients and heavy metals demonstrated there was an initial pulse of labile pollutants from the compost. However, when simulated stormwater containing typical concentrations of pollutants was added, there was no increase in pollutant leaching from the compost-soil blends compared to those receiving pure water. Thus, compost can be considered effective at removing the added load of nutrients and heavy metals found in roadside environments. The greenhouse vegetation experiment demonstrated there was no effect on germination with up to 100% compost from two different compost sources. Turfgrass biomass was increased with increasing compost rates (first at 10% compost then again at 100% compost). With the addition of just 10% compost, soil crusting was reduced and this aided in water penetration. Reduced soil crusting would help maintain infiltration at the field scale.

Based on our field study, increasing compost rates lead to increased infiltration rates, increased vegetation establishment, and reduced bulk density up to one year after compost application. Each increase in compost lead to an increase in vegetation establishment and a reduction in bulk density. It took compost application rates of only 10% to produce an increase in infiltration compared to control, but thereafter rates had to be further raised to 50% before additional improvement was observed.

Infiltration measurements from the field study suggest particle size of the compost may also be important factor in infiltration improvement. The commercial compost we included in our testing was finished with a finer screen, resulting in a smaller particle size similar to a soil with high organic matter. The uncertified compost contained 50% composted woody materials, which resulted in a mulch-like texture. The same amount of the coarser compost produced more than a 50% increase in infiltration compare to the finer compost, suggesting that the larger compost particle size produced more macropores for rapid infiltration. Further testing of this observation would be beneficial to determine if coarser compost could be used at a reduced rate to lower costs.

Our experiments used two different sources of compost: a certified compost (McGill SportsTurf®) and an uncertified compost (North Carolina State University Compost). The certified compost was STA certified by the U.S. Composting Council. While the two sources of compost performed similarly in the short-term greenhouse experiment, the certified compost outperformed the uncertified compost in vegetation establishment at field scale. Since a strong vegetation cover is desired, it is recommend that a STA certified compost be used in stormwater control measures for soil improvement. Alternatively, the compost can and should be tested to make sure it meets the requirements to be STA certified before application. Specifically, the specification for compost in stormwater control measures should make sure the C/N ratio, inorganic nitrogen and phosphorous (NH_4-N, NO_3-N, PO_4-P), pH, and heavy metals fall within the STA recommend guidelines.

We know that having good vegetation establishment is critical for long-term erosion and sediment control, and for infiltration of stormwater though root channels. While compost incorporation might not always directly improve infiltration rates, compost may provide longer-term benefits to degraded soils that make them more resilient to compaction from traffic, drought, and promote biological activity. Together this will improve the soil environment and allow it to function as an enhanced stormwater control measure. These results suggest that tilling a compacted soil may improve infiltration rates in sandy soils. However, a onetime certified compost application rate of 30% or higher may optimize soil improvement specifications in the following situations: (1) when good vegetation cover is critical, (2) in highly trafficked areas, and (3) in finer-textured soils.

RECOMMENDATIONS

- Tilling compacted soils is the most reliable way to improve soil physical and hydrological properties. Tilling the soil to a depth of 6 inches reduces the bulk density and increases infiltration rates compared to a compacted soil.
- Soils with higher sand contents and lower clay contents can use less compost to see benefits in infiltration rates. Compost application may be best suited to clayey soils where infiltration rates are known to be lower than sandy soils.
- Soil porosity is an important factor contributing to the infiltration rate of construction soils. Soils with higher porosities (low bulk densities) need less compost to see improvements in infiltration rates compared to soils with low porosities (high bulk densities). If the soil gets compacted, even at high rates of compost application (up to 50% by volume), the benefit of compost for infiltration is lost. After compost application, it is necessary to reduce traffic in these areas to maintain soil porosity.
- Compost particle size influences the infiltration rate of soils. Additional research is needed to specifically assess the effects of compost particle size on infiltration rate and to determine the longevity of effects.
- Certified compost blends at ≥10% by volume can improve vegetation establishment. The benefit of compost incorporation for vegetation establishment was found to persist for one year. Strong vegetation establishment is needed to maintain soil structure in order to reduce erosion and maintain infiltration benefits long-term.
- Compost can be used to filter stormwater. Certified compost blend at ≤ 50% compost by volume have the potential to retain certain pollutants when infiltrating stormwater, but this effect may decline over time. If compost is applied near sensitive water bodies, then water quality should be monitored.
- It is important to use a high-quality compost that is STA certified or meets the U.S. Composting Councils guidelines for STA certification.

IMPLEMENTATION

Our research results and recommendations can optimize soil improvement specifications to ensure a low-cost effective solution to the current BMP for highway stormwater management. We anticipate that NCDOT will be able to immediately implement our recommendations for tillage BMP on active and new construction sites. Compost incorporation should start to be included in the planning and budgeting of new and future construction projects. Implementation should come at relatively low cost compared to implementing other stormwater management practices such as built structures. Our results and recommendations should also inform decisions about maintenance and longevity of tillage and compost incorporation as stormwater management practices.

REFERENCES CITED

Agassi, M.; Hadas, A., Benyamini, Y., Levy, G.J., Kautsky, L., Avrahamov, L., Zhevelev, H., 1998. Mulching effects of composted MSW on water percolation and compost degradation rate. Compost Sci. Util., 6, 34–41.

Alshraah, S.H., 2020. Soil tillage for stormwater infiltration: Effects of amendments and vegetation type over time. PhD thesis. Department of Crop and Soil Sciences. North Carolina State University. Raleigh, NC.

Bartens, J., Day, S.D., Harris, J.R., Dove, J.E., Wynn, T.M., 2008. Can urban tree roots improve infiltration through compacted subsoils for stormwater management? J. Environ. Qual., 37, 2048–2057.

Batey, T., McKenzie, D.C., 2006. Soil compaction: Identification directly in the field. Soil Use Manag., 22, 123–131.

Bonnin, M. et al., 2006. *Precipitation-frequency atlas of the United States NOAA Atlas 14*, Volume 2, Version 3.0. NOAA National Weather Service, Silver Spring, MD.

Chahal, M.K., Shi, Z., Flury, M., 2016. Nutrient leaching and copper speciation in compost-amended bioretention systems. Sci. Total Environ., 556, 302–309.

Craul, P.J., 1994. Urban Soils: An Overview and Their Future in Landscape Below Ground; Wason, G.W., Neely, D., Eds.; International Society of Arboriculture: Savoy, IL, USA.

Crogger, C.G., 2005. Potential compost benefits for restoration of soils disturbed by urban development. Compost Sci. Util., 13, 243–251.

Crogger, C., Hummel, R., Hart, J., Bary, A., 2008. Soil and redosier dogwood response to incorporated and surface-applied compost. Hortscience, 43, 2143–2150.

Curtis, M.J., Claassen, V.P., 2009. Regenerating topsoil functionality in four drastically disturbed soil types by compost incorporation. Restor. Ecol., 17, 24–32.

Evanylo, G.K., Porta, S.N., Li, J., Shan, D., Goatley, J.M., Maguire, R., 2016. Compost practices for improving soil properties and turfgrass establishment and quality on a disturbed urban soil. Compost Sci. Util., 24, 136–145.

Hinman, C., 2009. Bioretention Soil Mix Review and Recommendations for Western Washington; Washington State University: Pullman, WA, USA. Available online: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.431.4124&rep=rep1&type=pdf (accessed on 7 November 2021).

Klute, A., 1986. Water retention: Laboratory methods. In: Klute, A., editor. Methods of Soil Analysis Part 1. Physical and Mineralogical Methods 2^{ed}, ASA-CSSA-SSSA, Madison, WI. p. 635-662.

Klute, A., and Dirksen, C., 1986. Hydraulic conductivity and diffusivity: Laboratory methods. In: Klute, A., editor. Methods of Soil Analysis Part 1. Physical and Mineralogical Methods 2^{ed}, ASA-CSSA-SSSA, Madison, WI. p. 687-734.

Logsdon, S.D., Sauer, P.A., Shipitalo, M.J., 2017. Compost improves urban soil and water quality. J. Water Resour. Prot., 9, 345–357.

Macnamara, J., Derry, C., 2017. Pollution removal performance of laboratory simulations of Sydney’s street stormwater biofilters. Water, 9 (11), 907.

Mohammadshirazi, F., McLaughlin, R.A., Heitman, J.L., Brown, V.K., 2017. A multi-year study of tillage and amendment effects on compacted soils. Journal of Environmental Management 203, 533-541.

Mohammadshirazi, F., Brown, V.K., Heitman, J.L., McLaughlin, R.A., 2016. Effects of tillage and compost amendment on infiltration in compacted soils. Journal of Soil and Water Conservation 71(6), 443-449.

NOAA National Centers for Environmental Information, 2019. State Climate Summaries: North Carolina. https://statesummaries.ncics.org/chapter/nc/#:~:text=Statewide%20average%20annual%20precipitation%20has,of%2068.4%20inches%20in%202018

Olson, N.C., Gulliver, J.S., Nieber, J.L., Kayhanian, M., 2013. Remediation to improve infiltration into compact soils. J. Environ. Manag., 117, 85–95.

Pitt, R., Lantrip, J., Harrison, R., Henry, C.L., Xue, D., 1999. Infiltration through Disturbed Urban Soils and Compost-Amended Soil Effects on Runoff Quality and Quantity; USEPA Report 600/R-00/016, NTIS PB2000-102012; Government Printing Office: Washington, DC, USA.

Reynolds, W.D., Elrick, D.E., 1990. Ponded infiltration from a single ring: I. analysis of steady flow. Soil Sci. Soc. Am. J., 54, 1233-1241.

Rivers, E.N., Heitman, J.L., Mclaughlin, R.A., Howard, A.M., 2021. Reducing roadside runoff: Tillage and compost improve stormwater mitigation in urban soils. J. Environ. Manag., 280, 111731.

Schafer-Landefeld, L., Brandhuber, R., Fenner, S., Koch, H.-J., Stockfisch, N., 2004. Effects of agricultural machinery with high axle load on soil properties of normally managed fields. Soil Tillage Res. 2004, 75, 75–86.

Shestak, C.J., Busse, M.D., 2005. Compaction alters physical but not biological indices of soil health. Soil Sci. Soc. Am. J., 69, 236–246.

Šimůnek, J., Šejna, M., Saito, H. Sakai, M., van Genuchten, M.T., 2013. *The HYDRUS-1D software package for simulation the movement of water, heat, and multiple solutes in variably saturated media*, Version 4.17. Department of Environmental Sciences, University of California Riverside, Riverside, CA, p. 343.

Subramaniam, D., Matherm P., Russell, S., Rajapakse, J., 2015. Dynamics of nitrate-nitrogen removal in experimental stormwater biofilters under intermittent wetting and drying. Journal of Environmental Engineering, 143 (3), 04015090. https:doi.org/10.1061/(ASCE)EE.1943-7870.0001043

Violin, C.R., Cada, P., Sudduth, E.B., Hassett, B.A., Penrose, D.L., Bernhardt, E.S., 2011. Effects of urbanization and urban stream restoration on the physical and biological structure of stream ecosystems. Ecol. Appl., 21, 1932–1949.

U.S. Composting Council, 2001. Composting testing programs. Available from: https://compostingcouncil.org /programs/ (accessed 03 May 2022).

U.S. EPA, 2003. Protection water quality from urban runoff. U.S. Environmental Protection Agency. Available from: https://www3.epa.gov/npdes/pubs/nps_urban-facts_final.pdf (retrieved 24 January 2019).

APPENDIX 1: THE EFFECTS OF COMPOST INCORPORATION ON SOIL PHYSICAL PROPERTIES IN URBAN SOILS – A CONCISE REVIEW

Please see attached file: Appendix 1.pdf

Kranz, C.N., McLaughlin, R.A., Johnson, A., Miller, G., Heitman, J.L., 2020. The effects of compost incorporation on soil physical properties in urban soils—A concise review. Journal of Environmental Management, 261, 110209. https://doi.org/10.1016/j.jenvman.2020.110209

APPENDIX 2: INFLUENCE OF COMPOST APPLICATION RATE ON NUTRIENT AND HEAVY METAL MOBILITY: IMPLICATIONS FOR STORMWATER MANAGEMENT

Please see attached file: Appendix 2.pdf

Draft manuscript accepted pending minor revisions for publication in Journal of Environmental Quality.

APPENDIX 3: CHARACTERIZING COMPOST RATE EFFECTS ON STORMWATER RUNOFF AND VEGETATION ESTABLISHMENT

Please see attached file: Appendix 3.pdf

Kranz, C.N., McLaughlin, R.A., Heitman, J.L., 2022. Characterizing compost rate effects on stormwater runoff and vegetation establishment. Water, 14, 696. https://doi.org/10.3390/w14050696

Journal of Environmental Management 261 (2020) 110209

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Review

The effects of compost incorporation on soil physical properties in urban soils – A concise review

Christina N. Kranz, Richard A. McLaughlin, Amy Johnson, Grady Miller, Joshua L. Heitman *

Department of Crop and Soil Sciences, North Carolina State University, Raleigh, NC 27695-7620, USA

ARTICLE INFO

Keywords:
Urban soil
Bulk density
Compost amendment
Infiltration
Soil physical properties
Disturbed soil

ABSTRACT

Incorporation of compost into soil can significantly alter soil physical properties, nutrient dynamics, and vegetation establishment. Strategic compost application to disturbed, degraded urban soil may provide benefits to soil properties. This review compared twenty-five peer-reviewed studies that evaluated changes in soil bulk density, infiltration rate, hydraulic conductivity, and water retention where compost was incorporated into urban soils. A wide range of compost rates and incorporation depths were evaluated in these studies across many soil types. Compost incorporation generally reduced bulk density, enhanced infiltration and hydraulic conductivity, and increased water content and plant available water, compared to unamended controls. In the four studies on runoff water quality, compost incorporation often resulted in higher initial nutrient content in runoff water, but also enhanced grass growth and reduced sediment loss. Few studies evaluated multiple compost application rates or incorporation depths, and the ways in which compost application rates were reported varied widely between studies making it difficult to directly compare them. Four studies investigated the long-term effects of compost incorporation, and there was no clear pattern of why some soils display enhanced physical properties over time and others do not. Compost was largely reported to have a positive effect on degraded urban soils. Little research has focused on the longevity of compost in urban soils after one application, and thus, this would be a valuable topic of further investigation.

1. Introduction

Soil erosion and stormwater runoff in urban areas are the biggest contributor to nonpoint source pollution according to the United States Environmental Protection Agency (U.S. EPA, 2003). Soil loss rates from construction sites can be 10 to 20 times those of agricultural lands (U.S. EPA, 2003). Urbanization can degrade the natural function of soil through vegetation removal, stripping of topsoil, and compaction by equipment (Crogger, 2005; Pitt et al., 1999). Development thus results in loss of soil organic matter (OM), increased bulk density, loss of soil structure, and reduced permeability.

Compost application to agricultural lands has been recognized as a reliable way to improve the physical properties of most soils, especially soils with poor structure and low levels of OM (Bauduin et al., 1987; Stratton et al., 1995). There has also been a widespread interest in using compost to amend urban soils post-disturbance in order to improve function (Albiach et al., 2000; Crogger, 2005). Documented changes in physical properties in compost-amended urban soils have included bulk density, infiltration rate, hydraulic conductivity, water content, aggregate stability, and porosity. These beneficial effects are interactive and are attributed to the compost materials applied and the amount of OM in the compost feedstock.

The goal of this review is to specifically highlight peer-reviewed studies that used compost incorporation into degraded urban soils. Compost incorporation, rather than simple surface application, has potential to alter soil properties in the subsurface but also requires additional soil disturbance. In an urban setting, where compost incorporation by processes such as tillage are not likely to be repeated frequently (e.g., annually), appropriate rates for a single compost application and the duration of associated changes in soil properties are particularly important. In general, appropriate compost rates have not been well-documented nor experimentally determined for improvement of degraded urban soils. Here, we define urban soil as a soil where a main soil disturbance (forming) factor has been humans and where the soil is not being used for agricultural production. Urban soils are those altered by human activities in the suburban or urban environment according the International Committee on Anthropogenic Soils (ICOMANTH, 2011). We also define compost as largely decayed organic

* Corresponding author. 3410 Williams Hall, North Carolina State University, Raleigh, NC 27695-7620, USA.
E-mail address: jlheitman@ncsu.edu (J.L. Heitman).

https://doi.org/10.1016/j.jenvman.2020.110209
Received 2 July 2019; Received in revised form 24 January 2020; Accepted 26 January 2020
Available online 1 February 2020

matter coming from recycled matter such as plant debris, and biosolids that are mature and stable. Our specific focus is on soils that have become degraded and compacted due to human activities associated with urbanization (such as construction); such soils have been subjected to major physical changes. Additionally, we do not include manure-only composts in our summary since there are few studies that have tested manure-only compost in urban soils, especially in construction or remediation projects. We also do not include any biochar compost mixtures in our review as biochar can be viewed as a compost-like amendment alternative, and biochar compost mixtures are relatively new with little research done on soil physical properties in urban settings. Lastly, in writing this paper, the word significantly means statistical hypothesis testing using a confidence interval of 95% where the p-value of 5% or lower is considered statistically significant.

In light of the rapidly expanding knowledge on compost incorporation to urban soils, we have undertaken a concise review to highlight key benefits, risks, and gaps in research. A number of reviews on compost incorporation are already available for agricultural soils (Amlinger et al., 2003; Beck-Broichsitter et al., 2018; Crogger, 2005; Diacono and Montemurro, 2009; Gallardo-Lara and Nogales, 1987; Hargreaves et al., 2008; Khlalee et al., 1981; Soane, 1990). Google Scholar and Web of Science search engines were used with the following combination key terms: urban soil, physical properties, hydraulic conductivity, bulk density, compost, infiltration, soil restoration, water retention, metal

Table 1
Effects of compost material on soil bulk density. All studies are in a non-agricultural setting and use some kind of compost and soil incorporation method. No manure compost studies included.

Compost feedstock[b]	Incorporation depth (cm)[c]	Application rate (s)	Soil type[d]	Effect	Time (years)[e]	Percent Change[f]	Reference
Mixed	15	0.75, 1.5, 3 cm[a]	Clay	Decreased	1	6, 12, 16	Aggelides and Londra (2000)
Mixed	15	0.75, 1.5, 3 cm[a]	Loam	Decreased	1	12, 18, 20	Aggelides and Londra (2000)
Mixed	28	11.2 cm[a]	Sandy loam	Decreased	5	15	Cannavo et al. (2014)
Yard waste	28	11.2 cm[a]	Sandy loam	Decreased	5	28	Cannavo et al. (2014)
Yard waste	60	10 cm	Loam	Decreased	5	No data	Chen et al. (2014)
Mixed	No data	1 cm	Loam	Decreased	3	9	Chen (2015)
Yard waste	20	7.6 cm	Sandy loam	Decreased	6	15	Crogger et al. (2008)
Yard waste	60	270, 540 Mg ha^{-1}	Loam	Decreased	2	No data	Curtis and Claassen (2005)
Yard waste	50	540 Mg ha^{-1}	Sandy loam (sandstone)	Decreased	1	20	Curtis and Claassen (2009)
Yard waste	50	540 Mg ha^{-1}	Loam (serpentinitic)	Decreased	1	19	Curtis and Claassen (2009)
Yard waste	50	540 Mg ha^{-1}	Sandy loam (lahar)	Decreased	1	20	Curtis and Claassen (2009)
Yard waster	50	540 Mg ha^{-1}	Sand (DG)	Decreased	1	21	Curtis and Claassen (2009)
Mixed	7 to 10	2.5, 5 cm	Sandy loam	Decreased	3	6, 11	Evanylo et al. (2016)
Yard waste	60	10 cm	Loam	Decreased	2	16	Layman (2010)
Sludge	10 to 15	1.3, 1.82 cm	No data	Decreased	1	No data	Loschinkohl and Boehm (2001)
Yard waste	30	5 cm	Fine sandy loam	Decreased	<1	55	Mohammadshirazi et al. (2016)
Yard waste	15 and 30	5 cm	Sand	Decreased	2	11, 15	Mohammadshirazi et al. (2017)
Yard waste	15 and 30	5 cm	Sandy clay loam	Decreased	2	14, 19	Mohammadshirazi et al. (2017)
Yard waste	30	5 cm	Sandy clay	Decreased	2	40	Mohammadshirazi et al. (2017)
Yard waste	30	5 cm	Clay loam (fill)	Decreased	2	11	Mohammadshirazi et al. (2017)
Mixed	122	15.24 cm	Unclassified	Decreased	12	39	Sax et al. (2017)
Yard waste	30	1.52, 6.04 cm[a]	Sandy loam	Decreased	2	15, 27	Schmid et al. (2017)
Yard waste	12.5	7.5 cm	Loam	Decreased	2	11	Schwartz and Smith (2016)
Sludge	20, 50	50% v/v	Loamy coarse sand	Decreased	1.5	27, 34	Somerville et al. (2018)
Sludge	20, 50	50% v/v	Coarse sandy loam	Decreased	1.5	27, 33	Somerville et al. (2018)
Sludge	20, 50	50% v/v	Loam coarse sand	Decreased	1.5	33, 23	Somerville et al. (2018)
Yard waste	25	7.2, 14.4 OM per hectare	Sandy loam	Decreased	4	22, 27	Tejada et al. (2009)
Yard waste	25	3.5, 7.2 OM per hectare	Sandy loam	Decreased	4	15, 19	Tejada and Gonzalez (2008)
Yard waste	25	3.5, 7.2 OM per hectare	Sandy loam	Decreased	4	28, 34	Tejada and Gonzalez (2008)
Yard waste	25	3.5, 7.2 OM per hectare	Sandy loam	Decreased	4	23, 29	Tejada and Gonzalez (2008)

[a] Unit conversions based on incorporation depth provided.
[b] Yard waste compost is used to refer to compost feedstock materials derived from plant-based materials such as law clippings, leaves, and wood. Sludge is used to refer to compost feedstock materials derived from biosolids or municipal solid waste. Mixed compost is used to refer to compost that uses a combination of sources.
[c] Incorporation can mean a variety of mechanisms to mix compost into the soil such as tilling, rototilling, subsoiling, hand plowing, or mixing on ground before addition to treatment plot.
[d] Soil textural class recorded when provided in original source material. When soil taxonomic name or soil series was given in source material, Web Soil Survey was used to determine the textural class.
[e] Time in years after the initial compost incorporation to the soil. If multiple measurements were taken over time, the longest time from the initial application was used.
[f] Where multiple entries are included, the order of reported percent changes follows the order of reported incorporation depth and/or application rate. The percent change was calculated from the last reported measurement, which correlates to the time reported in the preceding column. Chen et al. (2014) did not report exact bulk density values for all treatments of interest. Bulk density was only found to be significantly different at 15.2–20.3 cm. For Chen (2015) the percent decrease is an average of two sites with the same properties. Curtis and Claassen (2005) did not report any exact values for bulk density for the plots post-treatment. Loschinkohl and Boehm (2001) did not report exact values for bulk density for their plots post-treatment.

mobility, nutrients, and revegetation. The present review describes the direct and indirect influences of compost incorporation on various soil physical properties in degraded, compacted urban soils that may encourage improvements in overall soil function, stormwater management, and vegetation establishment.

2. Effects of compost on bulk density

Soils on construction sites are commonly compacted, resulting in an increased bulk density (Albiach et al., 2000; Layman, 2010). As bulk density increases, excessive soil strength occurs in dry conditions, and inadequate aeration can result when the soil is wet. Severe compaction can also limit root growth (Albiach et al., 2000; Crogger, 2005). Healthy roots function to anchor plants and to acquire and transport water, mineral nutrients, and oxygen from the soil pores to the leaves for photosynthesis. When root penetration and elongation are restricted by high bulk density, the volume of soil that can be exploited for essential nutrients and water is reduced, thus reducing overall plant growth. To help alleviate soil compaction, tilling and compost addition are two common practices often used. Eighteen peer-reviewed studies have reported on the effects of compost incorporation on bulk density for urban soils. Out of the 18 studies, all reported a reduction in bulk density compared to a control (Table 1). Not all studies reported exact bulk density values, so percent decreases could not be calculated for all 18 studies. Where appropriate, percent decreases are reported below.

Decreases in bulk density were observed in different soil types, at different application rates, at different incorporation depths, and with different compost feedstocks. In particular, Curtis and Claassen (2009) found that the bulk densities of four soils having different parent materials were reduced by 19–21% from a compacted control with the incorporation of 540 Mg ha^{-1} of compost to 50 cm deep in the soil profile. Their soil with decomposed granite parent material was the only soil that had a significantly (reduced by 9%) lower bulk density with compost incorporation compared to tilling alone. Aggelides and Londra (2000) also found a reduction in bulk density when incorporating a mixed compost 15 cm into both a clay and a loam soil. The greatest reduction in bulk density was at an application rate of 300 m^3 ha^{-1} for both the loam soil (19.7%) and the clay soil (16.7%). The incorporation depth for the 18 studies ranged from 7-10 cm–60 cm (Table 1). Another study compared three different soil types (two different loamy coarse sands and a coarse sandy loam) with a sludge compost application of 50% v/v (Somerville et al., 2018). All three soils had a reduced bulk density at both 3 (15–26% reduced) and 15 (14–25% reduced) months post compost application. This study used a deep tilling method and the soil was tilled to either 20 cm or 50 cm. The authors attribute some continued reduction in bulk density to the deep tilling method they used compared to other studies with shallower tilling depths.

Surface application of compost was found to reduce bulk density to a lesser extent compared to when the compost was incorporated 20 cm into the soil profile (Crogger et al., 2008). Both treatments received 7.6 cm of a yard waste compost, and the plots were planted with six species of container-grown plants to simulate the mixture of species found in the landscape. The incorporated compost plot had significantly lower bulk density (1.07 g cm^{-3}) than the surface applied compost (1.21 g cm^{-3}) 3.5 years after the application. Almost 6 years after the compost application, the bulk density of the surface applied compost (1.18 g cm^{-3}) was still significantly larger than the incorporated compost (1.04 g cm^{-3}), and the surface applied compost was not significantly different from the control treatment. When comparing the bulk densities of the incorporated compost at 3.5 years and 6 years, the values at 6 years were significantly lower than those at 3.5 years. The authors propose that the incorporation of compost directly diluted the soils with a low-density material and indirectly increased soil porosity.

Similarly, Mohammadshirazi et al. (2017) compared tillage with and without compost application to a compacted control soil. Plots were prepared in clay loam (fill material) and sandy clay soils using yard waste compost applied at 5 cm depth and incorporated to 30 cm and planted with grass seed mixtures recommended by the North Carolina Department of Transportation. The bulk density for the sandy clay with incorporated compost was significantly lower than the till only and compacted control at 7, 13, 19, and 26 months (55%, 51% 49%, and 40% respectively). The clay loam (fill material) bulk density with incorporated compost was also significantly lower at all sampling times (1–24 months) than the till only and compacted control (percent decrease in bulk density ranged from 19 to 65%). Mohammadshirazi et al. (2017) further compared compost incorporated to 15 and 30 cm depths across two soil types (sand and sandy clay loam) using a yard waste compost. There were no differences in bulk densities between the two incorporation depths over time (27 months for sand and 30 months for sandy clay loam). For the sand, the bulk densities of the incorporated compost treatments were significantly lower than the compacted soil at 1, 6, 23, and 27 months. The sandy clay loam was significantly lower than the compacted soil at 2, 3, and 23 months but not at 30 months.

Compost application rates were reported in several different ways in the literature with the most common being depth or weight per hectare. Several studies reported the amount of compost application by the ratio or volume of soil to compost or the amount of OM per hectare. Due to the differences in how the compost application rate was reported, it is challenging to directly compare application rates. On a volume basis, the lowest and highest application rate of compost that resulted in a reduction in bulk density were 0.75 cm (Aggelides and Londra, 2000) and 20 cm respectively (Bulmer et al., 2007). On a mass basis, the lowest and highest application rate of compost that resulted in a reduction in bulk density were 270 Mg ha^{-1} and 540 Mg ha^{-1} respectively (Curtis and Claassen, 2005, 2009). Since OM content is highly dependent on the feedstock of the compost, studies reporting compost application in terms of OM content are even more difficult to compare with these other studies.

In the studies reporting a reduction in bulk densities, the most common explanation was that the OM increased the void spaces leading to a decrease in the bulk density. Layman (2010) described this phenomena as the “fluff” effect on soil bulk density as OM has a lower density than the mineral fraction of soil. Overall, the literature suggests a clear trend of a reduced bulk density when incorporating compost into urban soils. It seems that the fluff effect can be lost over time in some soils, but there is no clear indication of why bulk density increased over time in some studies and not others.

3. Effects of compost on infiltration rate

Compacted urban soils have been reported to exhibit limited infiltration (Kelling and Peterson, 1975; Gregory et al., 2006). Reduced infiltration can result in ponding of water, increased runoff and erosion (Maniquiz et al., 2009). Ponding of water and increased runoff and erosion can inhibit the establishment of plant species (Maniquiz et al., 2009; Logsdon et al., 2017). The use of compost with tilling can alleviate these issues in urban soils (Agassi et al., 1998; Chen, 2015; Crogger et al., 2008; Logsdon et al., 2017; Pitt et al., 1999; Sax et al., 2017). Seven studies tested the effect of incorporated compost on infiltration rate. Six studies reported an increase in infiltration rate, and one study reported both an increase and no change in the infiltration rate (Table 2). The lowest percent increase was 24% in both Agassi et al. (1998) and in Logsdon et al. (2017). A 396% increase was recorded by Mohammadshirazi et al. (2017) for 5 cm yard waste compost incorporated 30 cm into a clay loam (fill). The lowest compost rate to produce a significant increase in infiltration rate was a 2 cm application rate in Agassi et al. (1998), and the largest application rate was 7.6 cm of a yard waste compost in Crogger et al. (2008). The shallowest incorporation depth that had a significant increase in infiltration rate was 5–10 cm in Logsdon et al. (2017), which reported 24 and 50% increases in infiltration rate for the two yard waste composts tested.

Using a rainfall simulator in the laboratory, Agassi et al. (1998)

Table 2
Effects of compost material on soil infiltration rate. All studies are in a non-agricultural setting and use some kind of compost and soil incorporation method. No manure compost studies included.

Compost feedstock[a]	Incorporation depth (cm)[b]	Application rate (s)	Soil type[c]	Effect	Time (years)[d]	Percent Change[e]	Reference
Sludge	No data	2 cm	Loam	Increased	1	24	Agassi et al. (1998)
Mixed	60	1 cm	Loam	Increased	3	162	Chen (2015)
Yard waste	20	7.6 cm	Sandy loam	Increased	4	250	Crogger et al. (2008)
Yard waste	5 to 10	5 cm	No data	Increased	4	24	Logsdon et al. (2017)
Yard waste	5 to 10	5 cm	No data	Increased	4	50	Logsdon et al. (2017)
Yard waste	30	5 cm	Sand	Increased	2	189	Mohammadshirazi et al. (2017)
Yard waste	30	5 cm	Sandy clay loam	Increased	2	359	Mohammadshirazi et al. (2017)
Yard waste	30	5 cm	Sandy clay	Increased	2	305	Mohammadshirazi et al. (2017)
Yard waste	30	5 cm	Clay loam (fill)	Increased	2	396	Mohammadshirazi et al. (2017)
Mixed	No data	2:1 soil: compost	Sandy loam	Increased	<1	No Data	Pitt et al. (1999)
Yard waste	20	2.5, 5, 7.5 cm	Loam	Increased	1	74, 100, 137	Weindorf et al. (2006)
Yard waste	20	2.5, 5, 7.5 cm	Clay loam	No significant change	1	–	Weindorf et al. (2006)
Yard waste	20	2.5, 5, 7.5 cm	Clay loam	No significant change	1	–	Weindorf et al. (2006)

Unit conversions based on incorporation depth provided.

[a] Yard waste compost is used to refer to compost feedstock materials derived from plant-based materials such as law clippings, leaves, and wood. Sludge is used to refer to compost feedstock materials derived from biosolids or municipal solid waste. Mixed compost is used to refer to compost that uses a combination of yard waste and sludge.

[b] Incorporation can mean a variety of mechanisms to mix compost into the soil such as tilling, rototilling, subsoiling, hand plowing, or mixing on ground before addition to treatment plot.

[c] Soil textural class recorded when provided in original source material. When soil taxonomic name or soil series was given in source material, Web Soil Survey was used to determine the textural class.

[d] Time in years after the initial compost incorporation to the soil. If multiple measurements were taken over time, the longest time from the initial application was used.

[e] Where multiple entries are listed, the order of reported percent changes follows the order of reported incorporation depth and/or application rate. The percent change was calculated from the last reported measurement, which correlates to the time reported in the preceding column. Agassi et al. (1998) is a laboratory study, and the percent change is an average of six simulated rainstorms over the course of 1 year. In Pitt et al. (1999), no control plot data were presented to make a comparison for a change in the infiltration rate.

investigated water percolation in loam soil amended with a sludge compost (2-cm application rate). A total of 260 mm of rainfall was applied over six consecutive rainstorms. The researchers found that 52% of the rainwater percolated into the soil with incorporated compost compared to 42% in the control and 85% with surface application of the same rate of sludge. At the laboratory scale, the incorporated sludge compost was found to provide efficient runoff control, but the surface applied compost performed better compared to the incorporated compost.

Crogger et al. (2008) compared surface applied compost with compost incorporated 20 cm into the soil profile over 6 years; yard waste compost from the same source and at the same rate was used in both application approaches. Both treatments significantly increased the infiltration rate of water compared to the control four years after the compost application. However, the surface applied compost had the same effect as the incorporated compost on infiltration rates with reported values of 1.7 mm min^{-1} and 2.1 mm min^{-1}, respectively, compared to 0.6 mm min^{-1} for the control. These study results suggest incorporation did not improve infiltration rate compared to surface application (especially when considering simplicity and cost of application).

Construction activities were simulated in a field study by Logsdon et al. (2017), in which the researchers examined the effects of yard waste compost incorporation (5-cm application rate, 5–10 cm incorporation depth) into the soil. There were no significant differences for time to runoff between incorporated and surface applied compost treatments, but there was a significant increase in time to runoff from the control with the incorporated and surface applied compost treatments. Prairie grasses (Buffalograss (*Buchloe dactyloides* (Nutt.) Engelm.) and Blue Grama grass (*Bouteloua gracilis* H.B.K.)) with compost had additionally reduced runoff and sediment loss compared to the same incorporated compost treatments planted with Kentucky bluegrass (*Poa pratensis* L.). The authors concluded that compost can increase infiltration.

Weindorf et al. (2006) also reported an increase in the infiltration rate for a loamy soil and no significant change in the infiltration rate for two clay loam soils when compost was incorporated. The authors indicated that soil texture, soil mineralogy, and climate effects were more important than the effect of the added compost. When comparing the studies that reported an increase in the infiltration rate, the lowest application rate was 1 cm compost incorporated to 60 cm (Chen, 2015) and the highest application rate was 7.5 cm compost incorporated to 20 cm (Weindorf et al., 2006).

Most studies attributed the increase in infiltration rate to the increased porosity and reduction in bulk density of the soil material with the addition of composted organic matter. There is a general trend of increasing infiltration rate with compost incorporation (Agassi et al., 1998; Chen, 2015; Crogger et al., 2008; Pitt et al., 1999; Schwartz and Smith, 2016; Weindorf et al., 2006), but several studies point out that infiltration rate is highly dependent on the texture of the soil being amended (Crogger et al., 2008; Weindorf et al., 2006). Most studies took infiltration measurements shortly after the plots were established (6–12 months). Only one study, Mohammadshirazi et al. (2017), measured infiltration rate >24 months after vegetated plots were established. In general, the infiltration rate remained significantly different from the control even two years after the compost incorporation.

4. Effects of compost on hydraulic conductivity

Reduced hydraulic conductivity of urban soils can inhibit vegetation reestablishment, which increases the chances of erosion as well as other environmental problems (Curtis and Claassen, 2009; Olson et al., 2013; U.S. EPA, 2003). Six studies investigated saturated hydraulic conductivity in soils with compost incorporation. All of the studies reported an increase (33–1100% across studies) in the saturated hydraulic conductivity compared to a compacted control except for two treatments in one study where they reported no significant change (Table 3). When reported as a depth, the lowest and highest compost application rate to have a significant increase in saturated hydraulic conductivity was 0.75 cm (55%, Aggelides and Londra, 2000) and 11.2 (835%, Cannavo et al., 2014), respectively. When reported on a mass basis, the highest compost application rate was 540 Mg ha^{-1} and it resulted in 64% increase in saturated hydraulic conductivity (Curtis and Claassen, 2009). Somerville et al. (2018) had the deepest incorporation depth at 50 cm, and they reported 1100% increase in the hydraulic conductivity. On the other hand, Aggelides and Londra (2000) had the shallowest incorporation depth at 15 cm, which led to 33% increase in the saturated hydraulic conductivity.

Curtis and Claassen (2009) found no significant change in the saturated hydraulic conductivity with compost incorporation in a sand and a sandy loam (sandstone parent material) soil. The authors attributed the lack of effects to parent material where the coarse texture helped maintain porosity for the degraded granite parent material and large cracks facilitated rapid infiltration for the sandstone parent material. Their lahar (102.8 mm h^{-1}) and serpentinitic (38.3 mm h^{-1}) parent material soils did have a significant increase in saturated hydraulic conductivity compared to the controls (62.8 mm h^{-1} and 25.9 mm h^{-1}, respectively). Yet there was no difference in saturated hydraulic conductivity for the incorporated compost treatments and the tilled only treatments.

On the other hand, Olson et al. (2013) found that incorporating compost resulted in higher saturated hydraulic conductivity than no treatment or tilling alone. Saturated hydraulic conductivity values were 1.8–5.6 times those of the controls across all three sites and soil types. Specifically, for their loam soil, the saturated hydraulic conductivity for the control, till, and incorporated compost treatments were 22.76, 12.71, and 30.74 cm h^{-1},respectively, three years after the initial compost application. Similarly, with their 'fill' soil, the average saturated hydraulic conductivities for the control, till, and incorporated compost treatments were 1.66, 3.24, and 10.19 cm h^{-1}, respectively, after three years. It is noteworthy that the two sites mentioned above had different soil textures and both continued to have increased saturated hydraulic conductivity three years post compost application.

Cannavo et al. (2014) measured saturated hydraulic conductivity with two different sources of compost: a mixed source and a yard waste source. When compared to a control, compost incorporation increased hydraulic conductivity by a factor of 22, but the incorporated yard waste compost treatment tended to have a faster reduction in hydraulic conductivity over time (5 years) than the mixed compost. The authors

Table 3
Effects of compost material on saturated and unsaturated hydraulic conductivity. All studies are in a non-agricultural setting and use some kind of compost and soil incorporation method. No manure compost studies included.

Compost feedstock[b]	Incorporation depth (cm)[c]	Application rate (s)	Soil type[d]	Effect	Time (years)[e]	Percent Change[f]	Reference
Saturated hydraulic conductivity							
Mixed	15	0.75, 1.5, 3 cm[a]	Clay	Increased	1	55, 97, 168	Aggelides and Londra (2000)
Mixed	15	0.75, 1.5, 3 cm[a]	Loam	Increased	1	33, 53, 95	Aggelides and Londra (2000)
Mixed	28	11.2 cm[a]	Sandy loam	Increased	5	750	Cannavo et al. (2014)
Yard waste	28	11.2 cm[a]	Sandy loam	Increased	5	835	Cannavo et al. (2014)
Yard waste	60	10 cm	Loam	Increased	5	567	Chen et al. (2014)
Yard waste	50	540 Mg ha^{-1}	Sandy loam (sandstone)	No significant change	1	–	Curtis and Claassen (2009)
Yard waste	50	540 Mg ha^{-1}	Loam (serpentinitic)	Increased	1	52	Curtis and Claassen (2009)
Yard waste	50	540 Mg ha^{-1}	Sandy loam (lahar)	Increased	1	64	Curtis and Claassen (2009)
Yard waster	50	540 Mg ha^{-1}	Sand (DG)	No significant change	1	–	Curtis and Claassen (2009)
Yard waste	40 to 45	7 cm	Loam	Increased	3	35	Olson et al. (2013)
Yard waste	40 to 45	7 cm	Loam	Increased	3	79	Olson et al. (2013)
Yard waste	40 to 45	7 cm	Fill	Increased	3	514	Olson et al. (2013)
Sludge	20, 50	50% v/v	Loamy coarse sand	Increased	2	400, 500	Somerville et al. (2018)
Sludge	20, 50	50% v/v	Coarse sandy loam	Increased	2	1060, 1100	Somerville et al. (2018)
Sludge	20 and 50	50% v/v	Loam coarse sand	Increased	2	163, 117	Somerville et al. (2018)
Unsaturated hydraulic conductivity							
Mixed	15	0.75. 1.5, 3 cm[a]	Clay	Decreased	1	N/A	Aggelides and Londra (2000)
Mixed	15	0.75, 1.5, 3 cm[a]	Loam	Decreased	1	N/A	Aggelides and Londra (2000)

[a] Unit conversions based on incorporation depth provided.
[b] Yard waste compost is used to refer to compost feedstock materials derived from plant-based materials such as law clippings, leaves, and wood. Sludge is used to refer to compost feedstock materials derived from biosolids or municipal solid waste. Mixed compost is used to refer to compost that uses a combination of yard waste and sludge.
[c] Incorporation can mean a variety of mechanisms to mix compost into the soil such as tilling, rototilling, subsoiling, hand plowing, or mixing on ground before addition to treatment plot.
[d] Soil textural class recorded when provided in original source material. When soil taxonomic name or soil series was given in source material, Web Soil Survey was used to determine the textural class.
[e] Time in years after the initial compost incorporation to the soil. If multiple measurements were taken over time, the longest time from the initial application was used.
[f] Where multiple entries are included, the order of reported percent changes follows the order of reported incorporation depth and/or application rate. The percent change was calculated from the last reported measurement, which correlates to the time reported in the preceding column. In Somerville et al. (2018) the data were estimated from a bar chart to calculate the percent change. Aggelides and Londra (2000) presented the unsaturated conductivity as a function of water content and no direct comparison for before and after can be made.

speculated that the difference, although not statistically significant, may have been due to higher fiber content in the yard waste compost.

Aggelides and Londra (2000) compared the effects of three different compost application rates incorporated to 15 cm on hydraulic conductivity in a clay and a loam soil. Increasing the compost application rate increased hydraulic conductivity, with this effect being more pronounced in the clay than the loam soil. Saturated hydraulic conductivity was increased by 32.5%, 53%, and 95.2% in the loam soil and 55.3%, 97.4%, and 168.4% in the clay soil with compost rates of 0.75 cm, 1.5 cm, and 3 cm, respectively. Chen et al. (2014) measured the effects of a compost application rate of 10 cm incorporated to 60 cm soil depth on hydraulic conductivity at different depths within a loam soil (referred to as the "PR treatment" by the authors). At 10–25 cm soil depth, hydraulic conductivity was twice that of the control, and at 25–40 cm soil depth it was as much as 10 times higher than the control. The authors speculated that the increase in saturated hydraulic conductivity was indirectly related to the increase in soil carbon since that can be an indication of soil aggregate formation. As with infiltration rate, there was a trend in the literature for incorporation of compost to increase saturated hydraulic conductivity.

Only one study measured the effects of compost incorporation on unsaturated hydraulic conductivity. Aggelides and Londra (2000) tested the effects of three different compost application rates (0.75, 1.5, and 3 cm) in a clay soil and a loam soil. The high rate (3 cm) of compost resulted in a reduction in the unsaturated hydraulic conductivity compared to those soils with low or no compost application. The reduction was less pronounced in the clay soil compared to the loam soil. However, the reduction was accompanied by an increase in water content. The authors suggested that the water retention ability of the two soils increased due to the increase in porosity with the addition of compost.

5. Effects of compost on water content

Compost is known to have a high water holding capacity and can provide water to plants over time (Crogger, 2005). Only three studies investigated the effects of compost incorporation on soil water retention, and all reported an increase in water retention of compost amended soils (Table 4).

Water content of lawns with compost incorporation was examined by Logsdon et al. (2017). A depth of 5 cm of a yard waste compost was incorporated 5–10 cm into the soil. Sets of lawns were compared with and without compost incorporation for a paired comparison over four years. From the 15 measurement dates over the four years, four dates showed significantly higher surface soil (1–6 cm) water contents in the incorporated compost lawns. Water contents for amended lawns ranged from 0.183 to 0.395 m^3 m^{-3}, and unamended lawns ranged from 0.193 to 0.339 m^3 m^{-3}, respectively. Both of the low water content values were taken in September, and the higher values were taken in March. Over time, three of the four paired lawns had significantly higher soil water content for the compost incorporation compared to an unamended control.

Aggelides and Londra (2000) compared water retention with different rates of a mixed source compost incorporated 15 cm into a clay and a loam soil. They found increased water retention with higher compost rates in both the clay and loam soil. Compost increased large pores especially the pores holding water at around 5 kPa tension for water retention. The clay soil tended to have higher water contents values at all pressures compared to the loam soil.

Schmid et al. (2017) investigated using yard waste compost and tillage on a compacted sandy loam. The researchers first used a subsoiler to incorporate the compost to 30 cm then used a rotadairon to further mix the compost and soil to 15 cm. The addition of 1.52 cm of compost resulted in a 6% increase in water content and a 6.04 cm compost addition increased it 9%, compared to the control. Twelve months after the compost application, the higher compost rate still had a significantly larger water content than did the lower compost application rate, while the lower rate was not different than the control. Fifteen month after the original compost application, neither compost application rate was found to be significantly different from the control. The authors speculated that the lack of differences might have resulted from an end of summer drought that had exhausted plant available water from all of the plots. Even the highest additions of compost did not fully prevent drought stress in the turf grass grown on top of the treatments.

6. Effects of compost on plant available water

Severe compaction in urban soils can make establishment and maintenance of plants difficult. Alleviating compaction prior to planting has been shown to lead to more persistent cover with reduced labor and

Table 4
Effects of compost material on water retention and plant available water in soils. All studies are in a non-agricultural setting and use some kind of compost and soil incorporation method. No manure compost studies included.

Compost feedstock[b]	Incorporation depth (cm)[c]	Application rate (s)	Soil type[d]	Effect	Time (years)[e]	Reference
Water retention						
Mixed	15	0.75, 1.5, 3 cm[a]	Clay	Increased	1	Aggelides and Londra (2000)
Mixed	15	0.75, 1.5, 3 cm[a]	Loam	Increased	1	Aggelides and Londra (2000)
Yard waste	5 to 10	5 cm	No data	Increased	3	Logsdon et al., 2017
Yard waste	30	1.52, 6.04 cm[a]	Sandy loam	Increased	2	Schmid et al. (2017)
Plant available water						
Mixed	20	101, 201, 301 Mg ha^{-1}[a]	No data	Increased	3	Black et al. (1999)
Yard waste	50	540 Mg ha^{-1}	Sandy loam (sandstone)	Increase	1	Curtis and Claassen (2009)
Yard waste	50	540 Mg ha^{-1}	Loam (serpentinitic)	No significant change	1	Curtis and Claassen (2009)
Yard waste	50	540 Mg ha^{-1}	Sandy loam (lahar)	No significant change	1	Curtis and Claassen (2009)
Yard waste	50	540 Mg ha^{-1}	Sand (DG)	Increased	1	Curtis and Claassen (2009)
Mixed	122	15.24 cm	Unclassified	Increased	12	Sax et al. (2017)

[a] Unit conversions based on incorporation depth provided.
[b] Yard waste compost is used to refer to compost feedstock materials derived from plant-based materials such as law clippings, leaves, and wood. Sludge is used to refer to compost feedstock materials derived from biosolids or municipal solid waste. Mixed compost is used to refer to compost that uses a combination of yard waste and sludge.
[c] Incorporation can mean a variety of mechanisms to mix compost into the soil such as tilling, rototilling, subsoiling, hand plowing, or mixing on ground before addition to treatment plot.
[d] Soil textural class recorded when provided in original source material. When soil taxonomic name or soil series was given in source material, Web Soil Survey was used to determine the textural class.
[e] Time in years after the initial compost incorporation to the soil. If multiple measurements were taken over time, the longest time from the initial application was used.

maintenance inputs (Carrow and Petrovic, 1992; Lichtner and Lindsey, 1994; Schmid et al., 2017). Three studies measured plant available water (PAW). Two studies reported an increase in PAW with compost incorporation use, while one study recorded both an increase and no change compared to a compacted control for the different soils they evaluated (Table 4). On a mass basis, the lowest and highest compost application rates were 101 (Black et al., 1999) and 540 Mg ha^{-1} (Curtis and Claassen, 2009), respectively. The shallowest incorporation depth that yielded a significant change in PAW was 20 cm (Black et al., 1999). For water retention, the lowest compost application rates were 0.75 cm (Aggelides and Londra, 2000). Schmid et al. (2017) had the highest reported compost rate (6.04 cm) and the deepest incorporation depth (30 cm) that produced a significant change in water retention. The shallowest incorporation depth was to yield a significant change in water retention was 5–10 cm (Logsdon et al., 2017).

Curtis and Claassen (2009) measured PAW in three different soils at an application rate of 540 Mg ha^{-1} and incorporated to 50 cm. Compared to the control, PAW decreased by about 20% in the sandy loam (with compost incorporation) with sandstone parent material. In soil with lahar parent material (sandy loam) and the serpentinitic parent material (loam), the PAW increased by about 30%. The authors concluded that PAW may be lower in course textured soils even with compost addition and moisture budgets need to be monitored.

Black et al. (1999) conducted a study with the Florida Department of Transportation to determine the effects of compost on PAW and turf establishment on Florida roadsides. The study included mixed compost at several application rates and incorporated to 20 cm. The PAW of compost amended plots was greater (12% increase) than unamended plots. Much of this increase was lost after about 6 months with the exception of the highest rate of 301 Mg ha^{-1}. The authors suggest the effect of the compost was due to better vegetation growth and less erosion at the study sites.

The Scoop & Dump (S & D) method was used to remediate soil on Cornell University's campus (Sax et al., 2017). A mixed source compost at a rate of 15 cm was incorporated 122 cm into the soil profile. When compared to the unamended control, the S & D soils had significantly higher PAW. On average, the S & D soils had a PAW of 0.22 m^3 m^{-3} and the unamended soils had a PAW of 0.15 m^3 m^{-3}. The bulk density was also reduced in S & D soils, which may be one of the reasons why there was an increase in PAW in amended soils. The increase in PAW was well correlated to the decrease in bulk density in this study. The authors additionally noted that the addition of organic matter can increase PAW and could be contributing to the increases recorded in the study.

7. Effects of compost on sediment, nutrient and heavy metal losses

Few studies have evaluated sediment loss and runoff water quality in urban soils being remediated with compost (Table 5). Mohammadshirazi et al. (2016) compared a deep tillage and deep tillage plus compost treatment to a compacted control in a fine sandy loam soil. The compost was applied at a rate of 5 cm and incorporated 30 cm into the soil profile. The researchers found there was no statistical differences in sediment loss between the deep till and the deep till plus compost except during one storm event. Compared to the compacted control, the deep till and deep till plus compost reduced sediment loss by 60%–76% respectively over the 6 month monitoring period. After the 6 month monitoring period, the total sediment loss was 202 kg ha^{-1} for the deep till plus compost, 120 kg ha^{-1} for the deep till, and 502 kg ha^{-1} for the compacted control. Both tilling treatments were found to be significantly smaller than the control, but the two tilling treatments were not statistically different from each other for the total sediment loss. The researchers noted that greater peak rainfall intensity generally corresponded to greater sediment loss in the compacted control.

Logsdon et al. (2017) measured runoff from rainfall simulations for nitrogen (N), phosphorus (P), and sediments. The treatment that received compost and was planted with prairie grass had significantly reduced P (total and ortho-P) and less sediment loss compared to the

Table 5
Effects of compost material on sediment, nutrient, and heavy metals losses in soils. All studies are in a non-agricultural setting. No manure compost studies included.

Compost feedstock[a]	Incorporation depth (cm)[b]	Application rate (s)	Soil type[c]	Time (years)[d]	Properties measured	Significant changes[e]	Reference
Sludge	No data	3.75 cm	Sandy clay loam	1	Total N, NO_3-N, total P, dissolved reactive P	Total N (59% decrease), NO_3-N (52% decrease)	Faucette et al. (2005)
Yard waste	No data	3.75 cm	Sandy clay loam	1	Total N, NO_3-N, total P, dissolved reactive P	Total N (67% decrease), NO_3-N (58% decrease)	Faucette et al. (2005)
Sludge	No data	3.75 cm	Sandy clay loam	1	Total N, NO_3-N, total P, dissolved reactive P	Total N (55% decrease), NO_3-N (72% decrease)	Faucette et al. (2005)
Yard waste	5 to 10	5 cm	No data	4	Sediment loss, ortho-P, ortho-P load, total ortho-P	Sediment loss (79% decrease), ortho-P load (86% decrease), total ortho-P (62% decrease)	Logsdon et al. (2017)
Yard waste	30	5 cm	Fine sandy loam	<1	Runoff, sediment loss	Runoff (82% decrease), sediment loss (60% decrease)	Mohammadshirazi et al. (2016)
Mixed	No data	2:1 soil: compost	Sandy loam	<1	Total N, total P, Cl, Al, Ca, Cu, Fe, K, Mg, Mn, Na, S, Zn, Si	None reported at the site level	Pitt et al. (1999)

Unit conversions based on incorporation depth provided.
[a] Yard waste compost is used to refer to compost feedstock materials derived from plant-based materials such as law clippings, leaves, and wood. Sludge is used to refer to compost feedstock materials derived from biosolids or municipal solid waste. Mixed compost is used to refer to compost that uses a combination of yard waste and sludge.
[b] Incorporation can mean a variety of mechanisms to mix compost into the soil such as tilling, rototilling, subsoiling, hand plowing, or mixing on ground before addition to treatment plot.
[c] Soil textural class recorded when provided in original source material. When soil taxonomic name or soil series was given in source material, Web Soil Survey was used to determine the textural class.
[d] Time in years after the initial compost incorporation to the soil. If multiple measurements were taken over time, the longest time from the initial application was used.
[e] Significant changes (increase or decrease) from a no compost control. Statistics were taken from the papers, and the percent changes were calculated from the data presented in the papers. The percent changes were calculated from the last time point available, which is reported in the preceding column. For Pitt et al. (1999), no significant differences were found at the site level, but significant differences were found between sites. Also, note that studies did not necessarily use the same measurement techniques for properties common between studies.

treatment that received top soil and a bluegrass mix. Sediment loss was 25 kg ha^{-1} h^{-1} for the compost treatment and 119 kg ha^{-1} h^{-1} for the topsoil plot. Ortho-P for the compost and topsoil were 0.62 mg L^{-1} and 1.08 mg L^{-1} respectively. The total and ortho-P for the compost and topsoil were 0.08 mg L^{-1} and 0.21 mg L^{-1} respectively. Nitrate levels were below detection levels in the supply water for both treatments.

On the other hand, Pitt et al. (1999) found runoff water quality was affected by leaching of nutrients from compost. Surface runoff from compost had higher total P, N, Cl, S, K, and Mg compared to a soil only treatment. Total Al, Fe, Mn, Zn, and Si had lower concentrations in the compost compared to the soil only treatments. In subsurface runoff, the compost had a higher concentration of total P, N, Cl, S, K, Mg, Al, Mn, and Si but had a lower concentration of Fe and Zn. Over six month, Pitt et al. (1999) found N and P in the surface and subsurface runoff decreased compared to the initial observation. The authors concluded that compost might increase concentrations of nutrients in runoff, especially when the site was newly developed.

Similarly, another study examined total N and P in runoff from an eroded sandy clay loam with different types of composts, all surface applied at the same rate (3.75 cm) (Faucette et al., 2005). The first simulated rain event (day 1) produced the highest rates of N and P runoff and the runoff rates decreased at their 3 and 12 month rainfall simulation events. On day 1, the N loads from the biosolids compost (4060 mg m^{-2}) and the municipal solid waste compost (2014 mg m^{-2}) were significantly higher than the control (bare soil, 76 mg m^{-2}). The yard waste compost (450 mg m^{-2}) did not differ in N loads on day 1 from the control. At the 3 month rainfall simulation, the N loads were significantly lower than at day 1 for the biosolids compost (254 mg N m^{-2}) and the municipal solid waste compost (23 mg N m^{-2}). The biosolids compost was not significantly different from the control (92 mg N m^{-2}) or the yard waste compost (38 mg N m^{-2}) at the 3 month rainfall simulation, but the municipal solid waste compost (23 mg N m^{-2}) was significantly lower than all other treatments. Nitrogen runoff from the biosolids was attributed to the high initial available N content of the compost compared to the yard waste compost. Likewise, the P loads were the highest on day 1 and were significantly reduced at the 3 month rainfall simulation. All three composts did not significantly differ from the control in total P loads on day 1, month 3, and month 12.

8. Effects of compost on establishment of grass cover

Organic amendments have long been used in turfgrass management to provide plant nutrients and to improve the physical, chemical, and biological properties of soil (Mccoy et al., 1986; Piper and Oakley, 1917). In the soil preparation phase of lawn establishment, compost is often mixed with the soil to improve the physical and chemical properties of the soil. A recommended ratio is to apply compost at a rate of 2.5–5 cm to the soil surface after which it is evenly incorporated to a depth of 10–15 cm just prior to seeding (Landschoot and McNitt, 1994).

Studies examining the various effects of composted material on soil properties and turfgrass have been conducted since the early 20th century. In general, the application of compost has been shown to have positive effects on turfgrass seed germination, turfgrass establishment, root growth, and on turf leaf color and density (Landschoot and McNitt, 1994; Linde and Hepner, 2005; Loschinkohl and Boehm, 2001; Mandal et al., 2013, Table 6). Compost can be beneficial in sod production as

Table 6
Effects of compost material on establishment of grass cover. All studies are in a non-agricultural setting and use some kind of compost incorporation method. No manure compost studies included.

Compost feedstock[a]	Incorporation depth (cm)[b]	Application rate (s)	Soil type[c]	Time (years)[d]	Properties measured[f]	Significant changes[e]	Reference
Mixed	7 to 10	2.5, 5 cm	Sandy loam	3	Biomass, turf color, turf density	Biomass (110% and 180% increase), turf color (53% and 76% increase), turf density (35% and 50% increase)	Evanylo et al. (2016)
Sludge	10 to 15	2.5, 5, 7.6 cm	Sandy loam	1.5	Turf cover, turf density, weed cover	Turf cover (87%, 92%, and 92% increase), turf density (142%, 218%, 221% increase), weed cover (50%, 75%, 100% decrease)	Linde and Hepner, 2005
Sludge	10 to 15	1.3, 1.82 cm	No data	1	Biomass, turf cover	Biomass (159% increase), turf cover (9% increase)	Loschinkohl and Boehm (2001)
Sludge	10 to 15	1.3, 1.82 cm	No data	1	Biomass, turf cover	Turf cover (6% increase)	Loschinkohl and Boehm (2001)
Sludge	10 to 15	1.3, 1.82 cm	No data	1	Biomass, turf cover	Biomass (23% increase), turf cover (10% increase)	Loschinkohl and Boehm (2001)
Mixed	12.7 cm	43, 87.5, 175 Mg ha-1	Silt loam	1	Biomass, turf cover, turf color, turf height	Biomass (250% increase for 175 Mg ha-1), turf cover (43%, 37%, 34% increase)	Mandal et al. (2013)
Mixed	12.7 cm	43, 87.5, 175 Mg ha-2	Silt loam	1	Biomass, turf cover, turf color, turf height	Biomass (400% increase for 175 Mg ha-1), turf cover (117%, 183%, 133% increase), turf color (18%, 37%, 47% increase)	Mandal et al. (2013)

Unit conversions based on incorporation depth provided.

[a] Yard waste compost is used to refer to compost feedstock materials derived from plant-based materials such as law clippings, leaves, and wood. Sludge is used to refer to compost feedstock materials derived from biosolids or municipal solid waste. Mixed compost is used to refer to compost that uses a combination of yard waste and sludge.

[b] Incorporation can mean a variety of mechanisms to mix compost into the soil such as tilling, rototilling, subsoiling, hand plowing, or mixing on ground before addition to treatment plot.

[c] Soil textural class recorded when provided in original source material. When soil taxonomic name or soil series was given in source material, Web Soil Survey was used to determine the textural class.

[d] Time in years after the initial compost incorporation to the soil. If multiple measurements were taken over time, the longest time from the initial application was used.

[e] Significant changes (increase or decrease) from a no compost control. Statistics were taken from the papers, and the percent changes were calculated from the data presented in the papers. The percent changes were calculated from the last time point available, which is reported in the preceding column. The order of percent changes for a given property is follows the order of values in the application rate column. Also, note that studies did not necessarily use the same measurement techniques for properties common between studies, and some measurements were based on a rating scale. For Mandal et al. (2013), values were taken from line plots to calculate percent changes.

[f] The first, second, and third lines reported for Loschinkohl and Boehm (2001) used a Kentucky bluegrass, perennial ryegrass, and a mixture of Kentucky bluegrass and perennial ryegrass, respectively. The first and second lines reported for Mandal et al. (2013) used a seeded grass and sodded grass, respectively.

well as the establishment of turfgrass on disturbed urban soils (Hornick et al., 1984). For example, Loschinkohl and Boehm (2001) demonstrated that amending a disturbed urban soil with 130 m^3 ha^{-1} biosolids compost to a depth of 10–15 cm significantly enhanced the establishment and growth of Kentucky bluegrass (*Poa pratensis*) and perennial ryegrass (*Lolium perenne*) compared to an un-amended control. Additionally, the application of 99–298 Mg ha^{-1} (40% moisture) compost and incorporated 10–15 cm into the soil has been recommended for optimal germination, establishment, and initial growth of turfgrass (Hornick et al., 1984). Hornick et al. (1984) additionally discussed that the application of 29–38 Mg ha^{-1} compost as a topdressing was capable of enhancing the establishment of cool-season grasses, especially in early spring and late fall seedlings.

A 3-year field study with a one-time compost incorporation application examined revegetation of a disturbed sandy loam soil (Evanylo et al., 2016). The compost was of mixed sources and incorporated in the plots at a rate of 2.5 cm or 5 cm depth. Plots were seeded with a mixture of 70% fescues (*Festuca arundinacea* Shreb.) 14% perennial ryegrass (*Lolium perenne* L.), 10% Kentucky bluegrass (*Poa pratenis* L.), and 4% unspecified. Turfgrass growth and quality (turf color) were improved in amended plots, and compost benefit increased over the study time. The rate of 5 cm of incorporated compost produced the highest amount of biomass.

Compost incorporation was additionally compared to surface applied compost (Evanylo et al., 2016). Incorporation had further improvements in turfgrass color in the first year but decreased over the rest of the study. This may be from a slower mineralization rate of surface applied compost compared to incorporated compost. Incorporation of compost seemed to maintain a better turfgrass quality than did the surface applied compost. In general, both surface and incorporated compost maintained better turfgrass color and densities than the controls. The authors concluded that compost can provide short and long-term turfgrass improvements, but compost may not need to be incorporated into the soil for best turfgrass performance.

9. Research gaps

In general, studies demonstrated a positive effect of compost incorporation on bulk density, infiltration, hydraulic conductivity, water retention, and PAW. However, several research gaps were identified. First, rates and depths of compost incorporation were not experimentally determined or optimized using laboratory or field experiments. Studies reported a wide range of compost application rates and incorporation depths. Few studies examined multiple compost application rates or incorporation depths, nor were there clear indications about how selected application rates and incorporation depths were identified. Presumably, rates would vary according to the source and characteristics of a compost. Systematic evaluation of compost rates and incorporation depths would help to determine how soil physical properties are altered as a function of compost application to disturbed urban soils. This type of research would help to identify optimal rates and incorporation depths to make it feasible for widespread adoption over a range of scenarios and performance goals.

Second, there is no standard for reporting compost study data. This makes it difficult to compare or generalize effects on soil properties across studies. Many studies were found to have missing or poorly reported compost information. The compost application rate was generally reported on either a mass or a depth basis. These two rates cannot be directly compared since the source of the compost greatly affects the density of the compost produced. Moisture content at time of application additionally affects the relationship between mass and depth (or volume). Kidder and Miller (1998) attempted to provide a method to standardize rates based on moisture and bulk density to quantify application rate and thickness for the Florida Department of Transportation recommended rate. A standardized way to report application rates and compost properties would allow for better comparison of study results.

Third, little is known of how long the effects of compost incorporation will last in degraded urban soils. Data on longevity of compost incorporation benefits are limited. Where available, results suggest that some of the effects of compost incorporation are still present as long as six years after the application. In situations where a one-time compost application is intended, three or more years of longer-term data on duration of associated soil physical property changes may be required to help with justification of costs of application.

10. Conclusion and future research

Most research to-date has focused on the effects of compost on soil physical properties in agricultural systems, and relatively little work has been done in an urban environment. Existing literature has shown improvement of soil physical properties such as bulk density, infiltration, and hydraulic conductivity with the addition of compost. Data on the longevity of compost benefits are limited, but suggest that some of the effects of compost are still present after five years. Most of the guidelines for compost use in urban environments have been based on research done in agricultural fields. Additional research on the effects of compost rate, incorporation depth, and compost source materials is needed to strengthen our understanding of how this organic amendment affects highly disturbed subsoils in a one-time application. This would strengthen the scientific basis for recommendations for improving degraded urban soils. Future research should focus on optimizing compost rates and incorporation depths to maximize soil physical properties for soil-water relations and vegetation reestablishment.

Acknowledgments

This work was funded by the North Carolina Department of Transportation, project authorization number RP2019-06.

References

Agassi, M., Hadas, A., Benyamini, Y., Levy, G.J., Kautsky, L., Avrahamov, L., Zhevelev, H., 1998. Mulching effects of composted MSW on water percolation and compost degradation rate. Compost Sci. Util. 6, 34–41.

Aggelides, S.M., Londra, P.A., 2000. Effects of compost produced from town wastes and sewage sludge on the physical properties of a loamy and a clay soil. Bioresour. Technol. 253–259.

Albiach, R., Canet, R., Pomares, F., Ingelmo, F., 2000. Microbial biomass content and enzymatic activities after the application of organic amendments to a horticultural soil. Bioresour. Technol. 75, 43–48.

Amlinger, F., Götz, B., Dreher, P., Geszti, J., Weissteiner, C., 2003. Nitrogen in biowaste and yard waste compost: dynamics of mobilization and availability-a review. Eur. J. Soil Biol. 39, 107–116.

Bauduin, M., Delcarte, E., Impens, R., 1987. Agronomic characterization and evaluation of two new municipal waste composts. In: De Bertoldi, M., Ferranti, M.P., L'Hermite, P., Zucconi, F. (Eds.), Compost: Production, Quality and Use. Elsevier Applied Science Publishers LTD, Barking, England, pp. 479–486.

Beck-Broichsitter, S., Fleige, H., Horn, R., 2018. Compost quality and its function as a soil conditioner of recultivation layers – a critical review. Int. Agrophys. 32 (1), 11–18.

Black, R.J., Kidder, G., Graetz, D.A., Miller, G.L., Dehgan, B., 1999. Evaluation of Composted Materials to Be Utilized in Florida Roadside and Median Plantings. WPI-0520743, Final Report. Department of Environmental Horticultural, Soil and Water Sciences Department, University of Florida.

Bulmer, C., Venner, K., Prescott, C., 2007. Forest soil rehabilitation with tillage and wood waste enhanced seedling establishment but not height after 8 years. Can. J. For. Res. 37, 1894–1906.

Cannavo, P., Vidal-Beaudet, L., Grosbellet, C., 2014. Prediction of long-term sustainability of constructed urban soil: impact of high amounts of organic matter on soil physical properties and water transfer. Soil Use Manag. 30, 272–284.

Carrow, R.N., Petrovic, M.A., 1992. Effects of traffic on trufgrass. In: Waddington, D.V., et al. (Eds.), Turfgrass, Agronomy Monograph 32. American Society of Agronomy, Crop Science Society of America, and Soil Science of America, Madison, WI, pp. 295–330.

Chen, S., 2015. Evaluation of Compost Topdressing, Compost Tea and Cultivation on Tall Fescue Quality, Soil Physical Properties and Soil Microbial Activity. MS Thesis. Department of Plant Sciences and Landscaping Architecture. University of Maryland, College Park, College Park, MD.

Chen, Y., Day, S.D., Wick, A.F., McGuire, K.J., 2014. Influence of urban land development and subsequent soil rehabilitation on soil aggregates, carbon, and hydraulic conductivity. Sci. Total Environ. 494–495, 329–336.

Crogger, C., Hummel, R., Hart, J., Bary, A., 2008. Soil and redosier dogwood response to incorporated and surface-applied compost. Hortscience 43, 2143–2150.
Crogger, C.G., 2005. Potential compost benefits for restoration of soils disturbed by urban development. Compost Sci. Util. 13, 243–251.
Curtis, M.J., Claassen, V.P., 2009. Regenerating topsoil functionality in four drastically disturbed soil types by compost incorporation. Restor. Ecol. 17, 24–32.
Curtis, M.J., Claassen, V.P., 2005. Compost incorporation increases plant available water in a drastically disturbed serpentine soil. Soil Sci. 170, 939–953.
Diacono, M., Montemurro, F., 2009. Long-term effects of organic amendments on soil fertility. A Rev. Agron. Sustain. Dev. 30, 401–422.
Evanylo, G.K., Porta, S.N., Li, J., Shan, D., Goatley, J.M., Maguire, R., 2016. Compost practices for improving soil properties and turfgrass establishment and quality on a disturbed urban soil. Compost Sci. Util. 24 (2), 136–145.
Faucette, L.B., Jordan, C.F., Risse, L.M., Cabrera, M., Coleman, D.C., West, L.T., 2005. Evaluation of stormwater from compost and conventional erosion control practices in construction activities. J. Soil Water Conserv. 60, 288–298.
Gallardo-Lara, F., Nogales, R., 1987. Effect of the application of town refuse compost on the soil-plant system: a review. Biol. Waste 19, 35–62.
Gregory, J.H., Dukes, M.D., Jones, P.H., Miller, G.L., 2006. Effect of urban compaction on infiltration rate. J. Soil Water Conserv. 61, 117–123.
Hargreaves, J.C., Adl, M.S., Warman, P.R., 2008. A review of the use of compost municipal solid waste in agriculture. Agric. Ecosyst. Environ. 123, 1–14.
Hornick, S.B., Sikora, L.J., Sterrett, S.B., Murray, J.J., Millner, P.D., Burge, W.D., Colacicco, D., Parr, J.F., Chaney, R.L., Willson, G.B., 1984. Utilization of Sewage Sludge Compost as a Soil Conditioner and Fertilizer for Plant Growth, Agriculture Information Bulletin. U.S. Department of Agriculture.
ICOMANTH, 2011. Circular Letter, Vol. 7. International Committee for Anthropogenic Soils. https://web.archive.org/web/20040811084031/http://clic.cses.vt.edu/icomanth/index.html. (Accessed 31 October 2019).
Kelling, K.A., Peterson, A.E., 1975. Urban lawn infiltration rates and fertilizer runoff losses under simulated rainfall. Soil Sci. Soc. Am. Proc. 39, 348–352.
Khlalee, R., Reddy, K.R., Overcash, M.R., 1981. Changes in soil physical properties due to organic waste applications: a review. J. Environ. Qual. 10, 133–141.
Kidder, G., Miller, G.L., 1998. Application Rates and Techniques for Using Compost Materials in Florida DOT Projects. SL-140. Soil and Water Science Department, Florida Cooperative Extension Service, Institute of Food and Agriculture Sciences, University of Florida.
Layman, R.M., 2010. Rehabilitation of Severely Compacted Urban Soil to Improve Tree Establishment and Growth Rachel Montgomery Layman. MS Thesis. Department of Crop and Environmental Soil Sciences. Virginia Polytechnic Institute and State University, Blacksburg, VA.
Landschoot, P., McNitt, A., 1994. Improving turn with compost. Biocycle 35, 54–57.
Lichtner, J.M., Lindsey, P.A., 1994. The use of surface treatments for prevention of soil compaction during site construction. J. Arborculture 20 (4), 205–209.
Linde, D.T., Hepner, L.D., 2005. Turfgrass seed and sod establishment on soil amended with biosolid compost. HortTechnology 15, 577–583.
Logsdon, S.D., Sauer, P.A., Shipitalo, M.J., 2017. Compost improves urban soil and water quality. J. Water Resour. Protect. 9, 345–357.
Loschinkohl, C., Boehm, M.J., 2001. Composted biosolids incorporation improves turfgrass establishment on disturbed urban soil and reduces leaf rust severity. Hortscience 36, 790–794.
Mandal, M., Chandran, R., Balasko, J., 2013. Amending subsoil with composted poultry litter-II: effects on Kentucky bluegrass (*Poa pratensis*) establishment, root growth, and weed populations. Agronomy 3, 670–684.
Maniquiz, M.C., Lee, S., Lee, E., Kong, D.S., Kim, L.H., 2009. Unit soil loss rate from various construction sites during a storm. Water Sci. Technol. 59, 2187–2196.
Mccoy, J.L., Sikora, L.J., Weil, R.R., 1986. Plant availability of phosphorus in sewage sludge compost. J. Environ. Qual. 15, 404–409.
Mohammadshirazi, F., McLaughlin, R.A., Heitman, J.L., Brown, V.K., 2017. A multi-year study of tillage and amendment effects on compacted soils. J. Environ. Manag. 203, 533–541.
Mohammadshirazi, F., Brown, V.K., Heitman, J.L., McLaughlin, R.A., 2016. Effects of tillage and compost amendment on infiltration in compacted soils. J. Soil Water Conserv. 71 (6), 443–449.
Olson, N.C., Gulliver, J.S., Nieber, J.L., Kayhanian, M., 2013. Remediation to improve infiltration into compact soils. J. Environ. Manag. 117, 85–95.
Piper, C.V., Oakley, R.A., 1917. Turf for Golf Courses. MacMillan Co., New York, NY.
Pitt, R., Lantrip, J., Harrison, R., Henry, C.L., Xue, D., 1999. Infiltration through Disturbed Urban Soils and Compost-Amended Soil Effects on Runoff Quality and Quantity. United States Environmental Protection Agency, Washington DC.
Sax, M.S., Bassuk, N., van Es, H., Rakow, D., 2017. Long-term remediation of compacted urban soils by physical fracturing and incorporation of compost. Urban For. Urban Green. 24, 149–156.
Schmid, C.J., Murphy, J.A., Murphy, S., 2017. Effect of tillage and compost amendment on turfgrass establishment on a compacted sandy loam. J. Soil Water Conserv. 72, 55–64.
Schwartz, S.S., Smith, B., 2016. Restoring hydrologic function in urban landscapes with suburban subsoiling. J. Hydrol. 543, 770–781.
Soane, B.D., 1990. The role of organic matter in soil compactibility: a review of some practical aspects. Soil Tillage Res. 16, 179–201.
Somerville, P.D., May, P.B., Livesley, S.J., 2018. Effects of deep tillage and municipal green waste compost amendments on soil properties and tree growth in compacted urban soils. J. Environ. Manag. 227, 365–374.
Stratton, M.L., Barker, A.V., Rechcigl, J.E., 1995. Compost. In: Rechcigl, J.E. (Ed.), Soil Amendments and Environmental Quality. Lewis Publ., Boca Raton. FL, pp. 249–310.
Tejada, M., Gonzalez, J.L., 2008. Influence of two organic amendments on the soil physical properties, soil losses, sediments and runoff water quality. Geoderma 145, 325–334.
Tejada, M., Hernandez, M., García, C., 2009. Soil restoration using composted plant residues: effects on soil properties. Soil Tillage Res. 102, 109–117.
U.S. EPA, 2003. Protection Water Quality from Urban Runoff. U.S. Environmental Protection Agency. Available from: https://www3.epa.gov/npdes/pubs/nps_urban-facts_final.pdf (retrieved 24 January 2019).
Weindorf, D.C., Zartman, R.E., Allen, B.L., 2006. Effect of compost on soil properties in Dallas, Texas. Compost Sci. Util. 14, 59–67.

Influence of Compost Application Rate on Nutrient and Heavy Metal Mobility: Implications for Stormwater Management

Christina N. Kranz[1], Erin N. Rivers[1,2], Richard A. McLaughlin[1], and Joshua L. Heitman[1*]

[1]*Department of Crop and Soil Sciences, North Carolina State University, Raleigh, NC 27696-7620, United States of America*

[2]*Department of Watershed Sciences, Utah State University, Logan, UT 84322-5200, United States of America*

*Corresponding author: jlheitma@ncsu.edu, Williams Hall 3410, 101 Derieux Place, Raleigh, NC 27607, United States of America

Core Ideas

- Compost-soil blends were dosed with stormwater to measure pollutant leaching and retention.
- Increasing compost rates increased mobility (reduced K_d) of phosphate and chromium.
- Simulated stormwater inputs did not increase leaching of pollutants compared to DI water.
- Compost influences pollutant transport and may retain most metals when infiltrating stormwater.

ABSTRACT

Amending soils with compost has become increasingly common in stormwater management practices. Compost can be a source and sink for nutrients and heavy metals, and it is important to understand the effect of compost on pollutant leaching under different hydrologic conditions. The objectives of this study were to (1) quantify the distribution coefficient (K_d) of nutrients (NH_4^+, NO_3^-, PO_4^{-3}) and metals (Cd, Cr, Cu, Ni, Pb, Zn) for compost-soil blends, and (2) examine how compost rate alters leaching patterns of pollutants from compost-soil blends. Material consisted of a sandy loam subsoil, a yard-waste compost, and compost-soil blends at 20% or 50% compost by volume. Materials were tested in sorption-desorption experiments using simulated stormwater (SW); columns with the materials were also leached with either SW or deionized (DI) water. As compost rate increased, the K_d for PO_4^{3-} and Cr decreased but increased for Cd, Cu, Ni, and Zn. The addition of compost reduced the sorption of PO_4^{3-} and Cr, potentially making it a source of these pollutants. Simulated stormwater did not increase the amount of pollutants retained compared to DI water for compost blends, except for 100% compost columns. Nitrate was the only constituent that had a negative removal efficiency, suggesting the compost was a source of NO_3^-. Column media retained more than 70% of the metals from the added stormwater solution. These results suggest that yard-waste compost blends at $\leq$ 50% have the potential to retain certain pollutants when infiltrating stormwater, but this effect may decline after several storm events.

Abbreviations: LID, Low Impact Development; PAH, Polycyclic Aromatic Hydrocarbons; DOM, Dissolved Organic Matter; SW, Simulated Stormwater; DI, Deionized; LOD, Limit of Detection

Keywords

Compost, Stormwater, Urban Soils, Nutrients, Heavy Metals, Water Quality, Sorption

INTRODUCTION

Ameliorating the harmful environmental impacts of stormwater runoff is an important consideration for urbanization. Low impact development (LID) practices are commonly used to reduce stormwater runoff and treat stormwater on-site, thereby improving water quality downstream (Davis, 2005). Low impact development practices are often decentralized and treat stormwater via detention and infiltration, and they have been shown to reduce runoff volume as well as nutrient and sediment loading compared to traditional stormwater practices (Dietz, 2007; Line et al., 2012; Wilson et al., 2015). Low impact development generally utilizes vegetated soil systems for runoff treatment, and compost amendment is becoming more popular in LID designs as a means to improve soil conditions for infiltration, plant growth, and pollutant filtration (Davis, 2005; Dietz, 2007). Compost has the potential to increase the infiltration rate of stormwater (Mohammadshirazi et al., 2017; Rivers et al., 2021), provide nutrients to vegetation, and may retain metals and organic pollutants (Hinman, 2009; NCDOT, 2014; Pit et al., 1999). However, compost can also be a source of nutrients and heavy metals depending on hydrologic conditions and compost source (Chahal et al., 2016; Mullane et al., 2015; Tirpack et al., 2021).

Using compost on roadsides is of particular interest where soils are heavily compacted from construction activities, and regulations require rapid infiltration and vegetation establishment (NCDOT, 2014). Runoff from roads contain heavy metals, inorganic nutrients, organic pollutants such as pesticides and microorganisms (Maestre & Pit, 2005). Of particular interest in compost amended roadsides are nitrogen (N) and phosphorous (P) because excess amounts of these nutrients in stormwater can cause eutrophication and groundwater contamination. Nitrogen is generally present in two inorganic forms, (nitrate (NO_3^-) and ammonium (NH_4^+)), and organically bound forms. Ortho-phosphate (PO_4^{3-}) is the most common and bioavailable form of P. Phosphorous can be adsorbed to soil particles through reactions with iron and aluminum (Klimeski et al., 2012).

Heavy metals such as cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn) are a primary concern for roadway stormwater management as they can be toxic to aquatic life (Maestre & Pit, 2005; Weiss et al., 2006). While heavy metals have been shown to be removed from stormwater infiltrating through compost blends (Davis et al., 2003; Dietz & Clausen, 2006), other studies have also shown that they are released from compost blends (Li & Davis, 2008; Mullane et al., 2015; Tirpak et al., 2021). Metals interact with organic matter by complexation; thereby compost can act as an effective adsorbent for metal ions in stormwater. However, compost also contains metals, and dissolved organic matter (DOM) released from compost can mobilize these metal ions (Maestre & Pit, 2005; Mullane et al., 2015). This dual role of organic matter can make compost-amended soils either a sink or a source of metals.

The heterogeneity of soil and compost makes it difficult to predict the potential mobility and distribution of pollutants. Adsorption and desorption experiments should be used together to find the potential of compost-soil blends to retain pollutants from stormwater. The distribution coefficient (K_d) is a useful parameter for comparing the sorptive capacities for different soil materials under the same experimental conditions. The K_d is commonly used with the premise that adsorption and desorption reactions are reversible. If compost is intended to filter stormwater, it is important to evaluate the adsorption capacity and the distribution between solid and solution phases to understand the mobility of pollutants (Shaheen et al., 2018; Jalali, & Jalili, 2011).

Nitrate, NH_4^+, PO_4^{3-}, Cu, and Zn are necessary for plant growth and can be supplied by the compost (Mahler, 2004), but in excess they can pollute urban stormwater (Maestre & Pit, 2005; Mullane et al., 2015; Tirpak et al., 2021). When compost is used to filter stormwater coming from roadsides, there is the potential for an additive effect of pollutants from both stormwater and compost. As compost incorporation becomes an increasingly popular method for soil improvement in urban stormwater systems, it is important to understand how the rate of compost addition affects pollutant retention versus export. Currently, there is no widely accepted standard of compost rate and composition for effective urban stormwater management (Crogger, 2005; Hurley et al., 2017; Kranz et al., 2020; Tirpak et al., 2021).

Our goal in this study was to examine mobility and export patterns of nutrients and metals for compost-soil blends through controlled laboratory experiments. First, we measured K_d of P and metals in soil, compost-soil blends, and compost with simulated stormwater (SW) to understand the relative distributions of pollutants between the solid and solutions phases. Next, SW and deionized water (DI) were used to leach columns containing soil, compost-soil blends, or compost. This allowed us to estimate the potential export of N, P, and metals from compost-amended systems during stormwater infiltration. We hypothesized that increased rates of compost would increase capacity to retain pollutants from stormwater. We additionally hypothesized that stormwater present in compost-amended systems would contribute to the export of pollutants by providing an additional pollutant source.

MATERIAL AND METHODS

Material Characterization and Preparation

A sandy loam subsoil (73% sand, 16% silt, and 11% clay) (Triangle Landscaping Supplies, Raleigh, NC) and a yard-waste compost (McGill SportsTurf®, New Hill, NC) were used to produce compost-soil blends. The compost provided by McGill is Seal of Testing

Assurance certified by the US Composting Council. A sandy loam soil was used as it is representative of common soil textures found on North Carolina roadsides (Alshraah, 2020; McLaughlin et al., 2013; McLaughlin & Knappe, 2018). Chemical analyses on the soil and compost were performed by Brookside Laboratories, Inc. (New Breman, OH) (Table 1, supplemental method S1).

Table 1. Chemical analysis for sandy loam soil and McGill SportsTurf® compost.

Property	**Soil**	**Compost**
Carbon (%)	0.78	17.54
Nitrogen (%)	0.05	1.30
C/N Ratio	15.60	13.49
pH[a]	4.70	7.00
Organic Matter (%)	1.65	20.74
Mehlich III Extractable P (mg kg^{-1})	11.00	254
Mehlich III Extractable Cu (mg kg^{-1})	0.82	0.46
Mehlich III Extractable Zn (mg kg^{-1})	1.41	18.64
NO_3-N (mg kg^{-1})	15.1	437
NH_4-N (mg kg^{-1})	9.40	3.50

[a]pH measurements were taken using 1:1ratio of water:material.

Helium (He) in a gas pycnometer (Micrometrics AccuPyc II 1340, Norcross, GA) was used to measure the particle density of each material or compost-soil blend after mixing. Using the measured particle density and a target porosity of 0.5 m^3 m^{-3}, corresponding target bulk density of each treatment was calculated by:

$$bulk\ density = (1 - porosity) \times particle\ density$$

for determining the mass of material to pack into columns for experiment 2. A consistent porosity was used to normalize the pore space across materials.

Experiment 1: Pollutant Distributions

The first experiment examined how the distribution of pollutants between solid and solution phases changed according to compost rate. Media used in this experiment were 0, 20, 50, and 100% compost by volume. All blends were mixed by hand on plastic sheets to obtain homogenous mixtures. A simulated stormwater solution (pH 6.9) was prepared as in Macnamara & Derry (2017) for metal concentrations and Subramaniam et al. (2015) for nutrient concentrations (Table 2). DI water was used as the base of the SW. Both studies based their simulated stormwater concentrations on median values from other studies.

Sorption experiments followed OECD guidelines 106 (2000). Adsorption potential was determined by mixing the media (0, 20, 50, and 100% compost by volume) with spiked stormwater solutions (0.01 M $CaCl_2$ solution with 1×, 4×, 8×, and 16× the SW concentration in Table 2). A ratio of 1:25 (kg L^{-1}) column media:solution was used in each centrifuge tube. Centrifuge tubes were shaken at a constant rate for 24-h on a shaker table. After 24-h, the suspensions were centrifuged (Eppendorf centrifuge 5810 R 15 amp version (Hamburg, Germany)) at 5000 rpm for 15 minutes, and the supernatant was filtered through a 0.45 μm pore size filter to remove solids. Desorption experiments were performed immediately after removing the supernatants by refilling the centrifuge tubes with 0.01 M $CaCl_2$ at a 1:25 (kg L^{-1}) media:solution ratio and following the same protocol as above. Equilibrium solutions from both phases were analyzed for dissolved phosphorous (PO_4^{-3}) and metals (Cd, Cr, Cu, Ni, Pb, Zn). Phosphorous was analyzed using a Lachat Quikchem® 8500 (Milwaukee, WI), and metals were analyzed using a Perkin Elmer Elan DRCII Inductively coupled plasma-mass spectrometer (Waltham, MA) using standard methods (Rice et al., 2012).

For each compost rate, regression models were constructed by plotting the pollutant in solution (C_e, mg L^{-1}) against the pollutant sorbed to the media (q_e, mg g^{-1}). The distribution coefficient (K_d) (L kg^{-1}) is the slope of q_e verses C_e and was calculated for both adsorption and desorption experiments. The K_d was defined as:

$$K_d = \frac{q_e}{C_e}$$

Table 2. Simulated stormwater concentrations.

Constituent	Source compound	Constituent concentration (mg L^{-1})
Cd	Cadmium chloride	0.013
Cr	Potassium chromate	0.05
Cu	Copper sulphate	0.14
NH_4-N	Ammonium nitrate	1.55
Ni	Nickel nitrate	0.07
NO_3-N	Ammonium nitrate, nickel and lead nitrates	0.40
Pb	Lead nitrate	0.30
PO_4-P	Trisodium phosphate	3.26
Zn	Zinc chloride	0.69

Experiment 2: Pollutant Export

The second experiment examined how rate of compost alters nutrient and metal retention versus export with simulated stormwater. Findings from supplemental method S2 guided the column leaching rate and the number of pore volumes collected. Briefly, flow rate was based on average draw down times for bioretention systems in North Carolina (Davis, 2009; Davis et al., 2008; Davis et al., 2006; NCDEQ, 2018). The number of pore volumes used was set based on the goal of supplying sufficient volume to capture the analyte export patterns, though this was not always achieved. Preliminary experiments indicated that four pore volumes were sufficient to capture patterns for some but not all analytes (supplemental Figure S1). Media used in this experiment were 0, 20, 50, and 100% compost by volume, as in experiment 1. Columns (15.24 cm tall and 7.62 cm diameter cylinders) were packed to a depth of 7.62 cm with the column media. The resulting treatment groups were deionized water (DI0, DI20, DI50, and DI100) and stormwater (SW0, SW20, SW50, and SW100) where the number refers to the percentage of compost. Triplicate analyses were performed on each treatment.

All columns were pre-saturated with DI water for one hour prior to the commencement of the leaching period to normalize starting conditions. Half of the saturated columns were leached with DI water, and the other half were leached with SW, both using a Mariotte bottle (Figure 1) to reach a final flow-through volume equivalent to six times the porosity. All columns were leached at a rate of 1.75 mL min^{-1}, equivalent to 1/10 pore volume of leachate collected every 10 minutes, for a total of 10 hours. Constant head and flow rate were maintained with a peristaltic pump (Figure 1). Six pore volumes of leachate were collected from each column in 1/10 fractions using a fraction collector (Eldex® Universal Fraction Collector, Napa, CA). Samples were analyzed for dissolved nutrients (NH_4^+, NO_3^-, PO_4^{-3}) and metals (Cd, Cr, Cu, Ni, Pb, Zn) as in experiment 1. Separate export curves were created for each constituent.

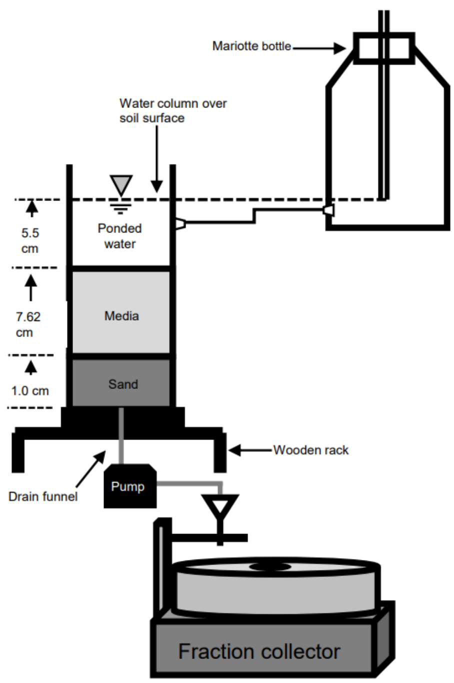


Figure 1. Schematic diagram of column experiment. The drawing is not to scale.

Statistical Analysis

All statistical analyses were performed in R version 4.1.2 (R Core Team, 2021). For experiment 1, adsorption and desorption curves were fitted using linear regression, and K_d was calculated as the slope of the line. For experiment 2, export curves were generated for each analyte in the leachate collected for both DI and SW columns. If a value was below the limit of detection (LOD), the LOD divided by the square root of two was used in calculations (Boss & Rix, 2020). The total export of each analyte was determined as the area under the export curve and was calculated using trapezoidal integration in the *pracma* package (Borchers, 2020). A factorial (2 x 4) analysis of variance (ANOVA) with least significant differences (LSD) was used to evaluate significant differences between treatments ($p<0.05$).

RESULTS AND DISCUSSION

Experiment 1: Pollutant Distributions

The effectiveness of compost for sorbing pollutants from stormwater was investigated. The K_d was controlled by the compost rate for all pollutants for both sorption and desorption. As the amount of compost increased, the amount of water soluble PO_4^{3-} increased as indicated by the decreasing K_d values (Table 3). Phosphate levels were below detection for the 0% compost indicating the soil has a high capacity to sorb PO_4^{3-}. The desorption PO_4^{3-} K_d values also decreased with increasing compost rate and were higher than their respective sorption values. Phosphate was not detected in the desorption 0% and 20% compost treatments, indicating the PO_4^{3-} most likely remained sorbed to the media. The K_d was 5-6 times greater for the 50% than the 100% compost. Several other studies using compost to amend soils concluded that organic matter in compost might prevent the sorption of PO_4^{3-} (Horta, 2019; Ramos et al., 2021). Less compost would reduce the likelihood of PO_4^{3-} leaching when used to filter stromwater. The PO_4^{3-}

content of compost should be limited to prevent excess PO_4^{3-} leaching in stormwater practices (McPhillips et al., 2018).

Table 3. Distribution coefficients (K_d) for the amended soil for competitive sorption.

	Adsorption K_d (L kg^{-1})													
	PO_4		**Cd**		**Cr**		**Cu**		**Ni**		**Pb**		**Zn**	
Compost rate (%)	K_d	R^2	K_d	R^2	K_d	R^2	K_d	R^2	K_d	R^2	K_d	R^2	K_d	R^2
0	N.D.	--	0.2	0.28	22.4	0.75	5.0	0.74	2.3	0.63	N.D.	--	0.8	0.93
20	16.2	0.95	1.4	0.94	21.6	0.73	8.1	0.86	8.6	0.56	N.D.	--	5.5	0.81
50	7.8	0.89	3.5	0.94	17.6	0.92	9.1	0.78	9.4	0.49	N.D.	--	16.2	0.94
100	1.3	0.78	4.3	0.95	12.9	0.95	11.4	0.90	11.5	0.59	N.D.	--	23.1	0.94
Compost rate (%)	Desorption K_d (L kg^{-1})													
0	N.D.	--	0.6	0.89	145.6	0.72	5.2	0.76	35.2	0.93	123.3	0.80	0.8	0.83
20	N.D.	--	1.4	0.92	N.D.	--	N.D.	--	18.7	0.97	N.D.	--	6.3	0.95
50	56.8	0.74	4.8	0.97	N.D.	--	N.D.	--	N.D.	--	N.D.	--	52.8	0.86
100	11.2	0.98	14.4	0.88	N.D.	--	N.D.	--	N.D.	--	N.D.	--	117.8	0.91

[a]N.D. is no detection. Detection limit was < 0.01 mg PO_4^{3-}/L, <1.5 µg Cr/L, <3.2 µg Cu/L, <3.5 µg Ni/L, <15.0 µg Pb/L.

Sorption K_d values for heavy metals exhibited different responses to compost. Increased compost content increased K_d for Cd, Cu, Ni, and Zn, while having the opposite effect on Cr (Table 3). Lead was not detected in supernatant for any compost rate for the sorption experiments indicating the compost and soil have a high capacity to sorb Pb. The desorption K_d increased with increasing compost rate for Cd and Zn. Chromium, Cu, and Pb were only detected in the supernatant for the 0% compost desorption experiments. Nickel was detected for the 0% (35.2 L kg^{-1}) and 20% (18.7 L kg^{-1}) compost rates. These experiments indicate that compost retained Cr, Cu, Ni and Pb during the desorption process. Detectable desorption K_d values were generally larger than their respective sorption K_d value (Table 3).

Christensen (1985) mixed a sandy loam soil with two different composts and measured Cd sorption. Their Cd K_d (5.2-6.5) was similar to that obtained in this study for the 50% and 100% compost. Jalali & Jalili (2011) added a compost to calcareous soils and measured K_d for Cd, Cu, Ni, and Zn. Their reported Cd and Zn K_d values were similar to the ones reported in this study for 50% and 100% compost. However, their Cu values were 11-17 times the K_d reported here, and the K_d for Ni reported here are 2-6 times their values. Their soil had a higher pH (7.2-7.6) compared to the soil used in this experiment (4.7). The higher K_d values reported by Jalali & Jalili (2011) are likely from the higher soil pH, as soil pH is a main factor governing sorption potential of metals in soil (Kashem & Singh, 2001; Sauvé et al., 2000). Soil pH and compost source may play a critical role in the competitive sorption of heavy metals. The present results indicate that the addition of compost to a sandy loam soil reduced the sorption of Cr, while increasing the sorption of other metals. Reduced sorption of Cr can be attributed to its anionic form present in the soil. Thus, as compost rate increases, the pH of the compost-soil blend increases, resulting in reduced sorption of Cr (Banks, et al., 2006; Choppala et al., 2018; Xu et al., 2020). Heavy metals were generally retained on the media during the desorption experiments. Compost amendment rate influences soil pH and organic matter content, which in turn influence the storage and retention of metals. Compost may help soils retain most metals when infiltrating stormwater.

Experiment 2: Pollutant Export

Ortho-phosphate

Export of PO_4^{-3} was significantly higher from 100% compost columns compared to the other treatments (Figures 2 & 3). There was a lag period in the release of PO_4^{-3} from all columns followed by an increase at 2.5 pore volumes (Figure 2). The DI100 and SW100 peaked at pore volume 5.5 with concentrations of 3.5 mg L^{-1} and 3.8 mg L^{-1}, respectively. The total export of SW100 (5.1 mg kg $media^{-1}$) was higher than that of DI100 (4.7 mg kg $media^{-1}$) ($p<0.05$, Figure 3). Total PO_4^{-3} export did not differ between leaching agents for other compost rates. Concentrations of PO_4^{-3} were highest with 100% compost likely because of high P content in the compost, which was 23× higher than in the soil (Table 1). The SW100 exported 17% of the PO_4^{3-} in the simulated stormwater solution, resulting in 83% retention (Figure 4). All other treatments retained more than 98% of the starting PO_4^{3-} concentration.

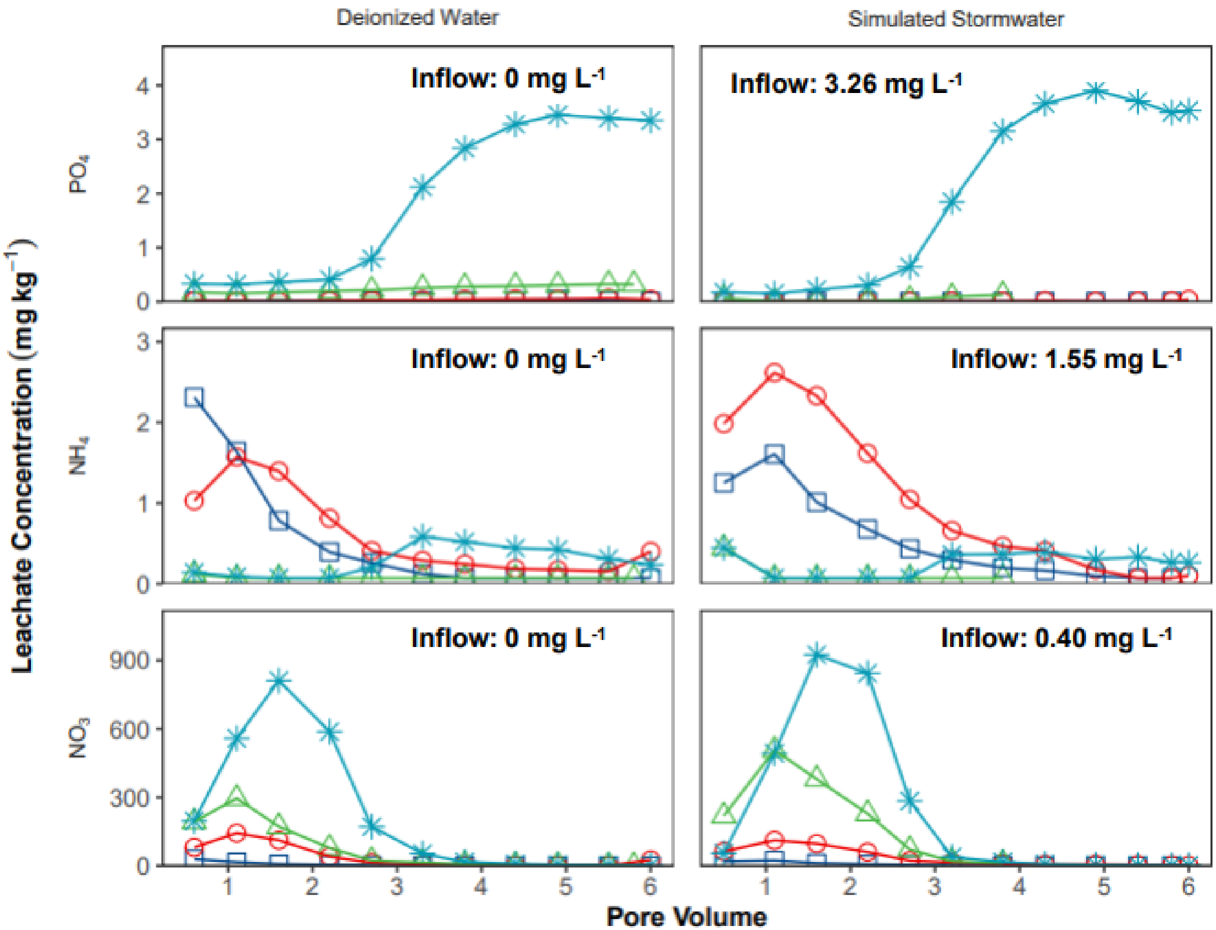


Figure 2. Concentration of nutrients in leachate from experimental columns in pore volume fractions. Six pore volumes of deionized water and simulated stormwater were leached at a rate of 1.75 mL min^{-1} (1/10 pore volume of leachate collected every 10 minutes). Error bars and letters of significance omitted for visual clarity.

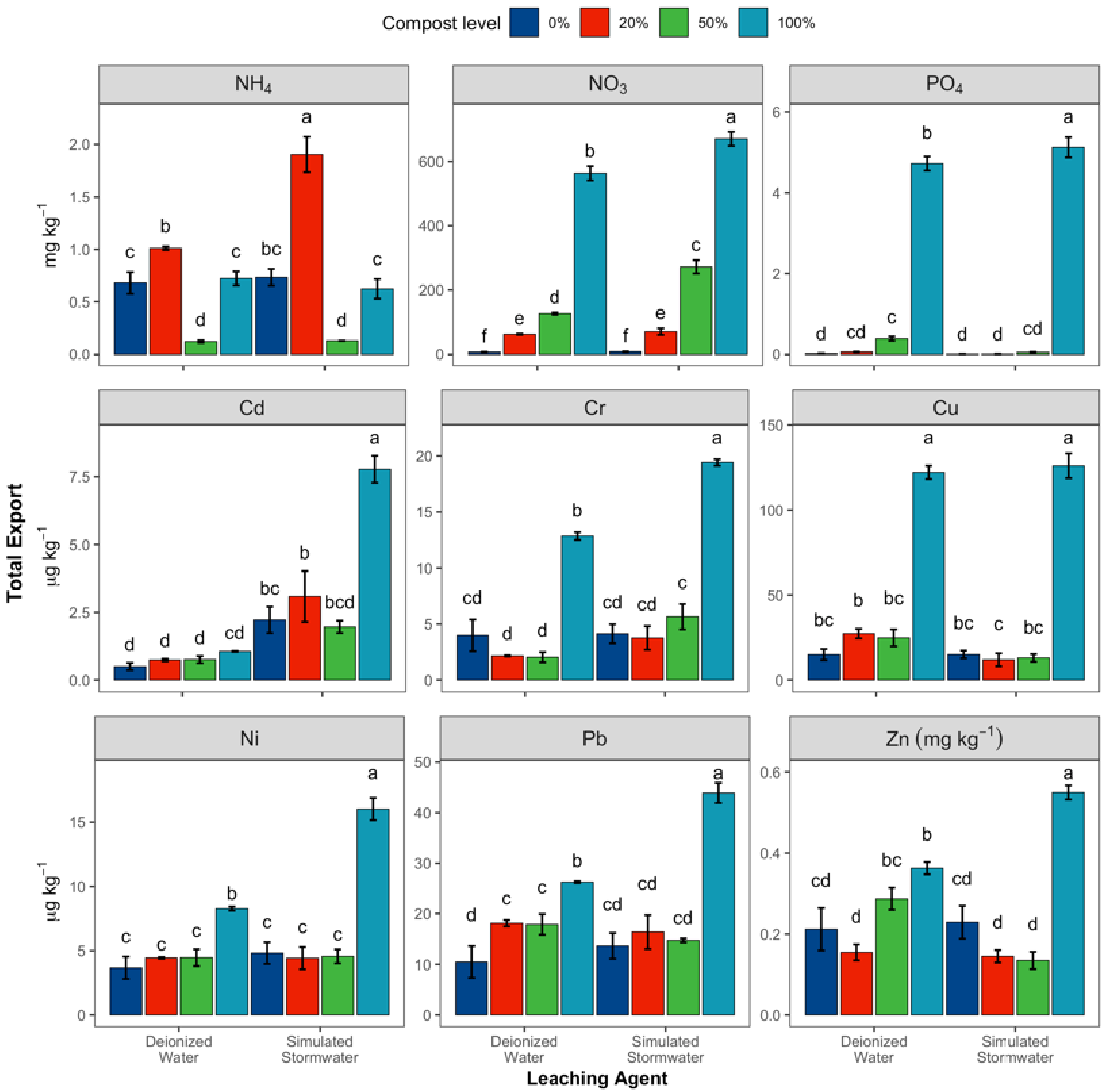


Figure 3. Total mass (±SE) of nutrients and heavy metals exported from experimental columns leached with deionized water and simulated stormwater. Letters indicate significant differences between treatments within each pollutant (LSD, $p < 0.05$).

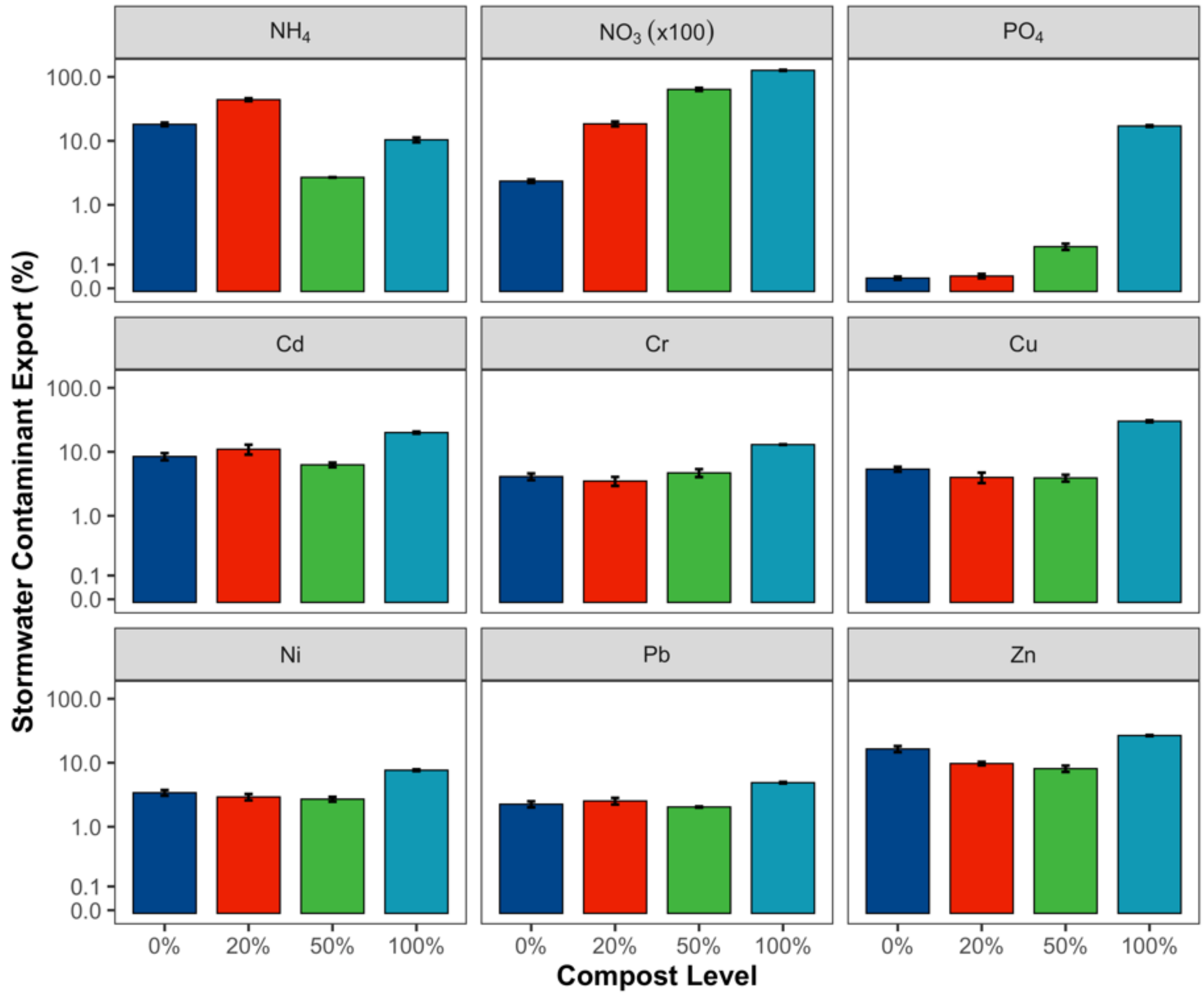


Figure 4. Export (±SE) of nutrients and heavy metals from experimental columns as a fraction of total added in simulated stormwater. The (×100) means the values should be multiplied by 100 to get the measured values. Values exceeding 100% (nitrate) indicate contributions from the matrix.

The leaching pattern of PO_4^{-3} observed in this experiment is similar to other studies (Xia et al., 2007; Li et al., 2013), where there was lag period followed by a continued increase across several pore volumes. The maximum PO_4^{-3} concentrations reported in this study [4.7 mg kg media^{-1} (DI100), 5.1 mg kg media^{-1} (SW100)] are 70-85% lower than values reported in similar studies with yard-waste compost (Chahal et al., 2016; Mullane et al., 2015), likely due to compost source. However, several studies demonstrate that PO_4^{3-} levels continue to decline with time due to media sorption potential, other biogeochemical processes, and environmental factors (Hunt et al., 2006; Mullane et al., 2015; Rivers et al., 2021; Xia et al., 2007). McPhillips et al. (2018) suggested using ≤15% organic matter to reduce the chance of PO_4^{3-} leaching. When compost blends were leached with SW, the total PO_4^{3-} export did not increase relative to DI columns (Figure 3). This experiment demonstrated that compost blends have the ability to retain much of the PO_4^{3-} from SW.

Ammonium

Export of NH_4^+ was highest from SW20 at 1.9 mg kg media^{-1} ($p<0.05$, Figure 3) and lowest from DI50 and SW50 at 0.1 mg kg media^{-1}. The high concentrations of NH_4^+ occurred within the first 1/10 pore volume followed by a decrease in NH_4^+ concentrations, except for the DI20 and SW20 (Figure 2). Peak concentrations in the 20% compost columns occurred at pore volume one before decreasing to soil levels. A second flush of NH_4^+ occurred in both DI100 and SW100 with peak concentrations at pore volume four before declining to soil levels. The NH_4^+ concentrations were the same at the end of the experiment for all treatments ($p<0.05$).

The soil used in this experiment had a higher concentration of NH_4^+ (9.40 mg kg^{-1}) compared to the compost (3.50 mg kg^{-1}), which could explain the differences in NH_4^+ export for the SW20. The labile NH_4^+ was flushed out of the soil within the first pore volume before declining to a steady concentration. The second flush of NH_4^+ from the 100% compost columns was likely attributed to the conversion of organically bound nitrogen to ammonium, which occurs under both aerobic (via ammonification) and anaerobic (via anammox) conditions. The compost columns likely have higher microbial activity, so with increased saturation time, the microorganisms were more likely to facilitate microbial conversions of organic- to inorganic-N to produce the second flush. Hurley et al., (2017) found that as saturation time increased, compost blends exported significantly more NH_4^+ regardless of compost feedstock. Additionally, two of their mixed sourced composts saturated for either 10 minutes or 24 hours had similar NH_4^+ concentrations to the ones reported here. The addition of SW produced a significant increase in export from the 20% compost blend, which exported the highest total amount of NH_4^+, or 44% of the added NH_4^+ (Figure 4).

Nitrate

Export of NO_3^- was highest from SW100 at 670 mg kg media^{-1} followed by the DI100 at 563 mg kg media^{-1} (Figure 3). Export was lowest from the soil-only columns at 7.0 mg kg media^{-1} (DI0) and 8.4 mg kg media^{-1} (SW0). Peak NO_3^- concentrations from SW compost columns occurred at pore volume two followed by a decline to soil levels (Figure 2). Peak concentrations from DI columns occurred between pore volume one and two. In general, more NO_3^- was leached with increasing compost content and with SW. At the last time point, all of the NO_3^- concentrations were the same ($p<0.01$, Figure 2).

Nitrate was the only constituent that exported a higher rate than what was added from the SW (Figure 4). The 100%, 50%, 20%, and 0% compost exported 127×, 64×, 18×, and 2× more NO_3^- than was present in the SW, respectively. The pattern of increasing NO_3^- concentration and export as compost content increased can be attributed to the high amount of NO_3^- in the compost

(437 mg kg^{-1}) compared to the sandy loam soil (15.1 mg kg^{-1}) (Table 1). The amount of NO_3^- leached from each treatment is likely reflective of the amount of NO_3^- in the treatment at the start of the experiment. This suggests that compost nitrate levels should be measured before choosing a source to use in stormwater practices.

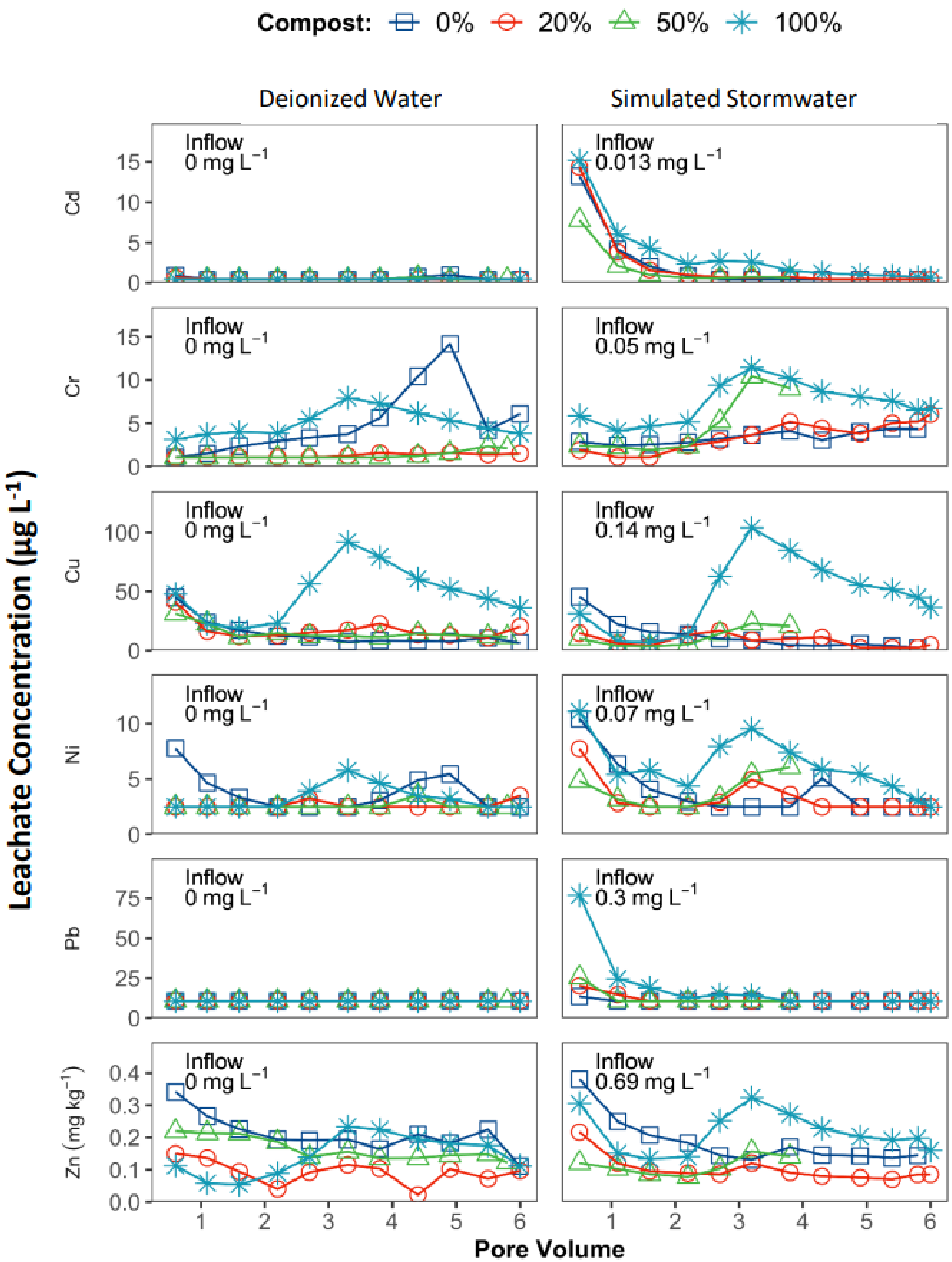
Two studies using a similar compost also reported that most of the NO_3^- was exported from the system within the first few pore volumes (Chahal et al., 2016; Mullane et al., 2015). Nitrate concentrations in these studies were 28 to 53% lower than the concentrations reported in this experiment. However, their compost NO_3^- levels were lower than the compost used in this experiment. Another study using a biosolid yard-waste compost had higher peak NO_3^- concentrations in leachate for their compost (1996 mg L^{-1}) and compost blend (1022 mg L^{-1}) columns, but the compost also started with higher NO_3^- levels (Xia et al., 2007). Compost source and its C:N ratio might affect the leaching.

Heavy Metals

Cadmium and Pb followed a similar export pattern, but different from that of Cr, Cu, Ni, and Zn (Figure 5). When SW was used to leach the columns, there was an initial flush of all heavy metals followed by a decline. Cadmium and Pb continued to decline until the end of the experiment, and all compost rates had the same concentration of Cd or Pb at pore volume six ($p<0.01$). Chromium, Cu, Ni, and Zn had a second flush between three and four pore volumes followed by a continual decline to the end. The second flush of metals had higher peak concentrations in the SW versus the DI columns and increased with increasing compost rate.

Total export of all metals was highest in SW100 (Figure 3). The total export of each metal from the SW100 treatment was 7.8 µg Cd kg $media^{-1}$, 19.4 µg Cr kg-$media^{-1}$, 15.1 µg Cu kg $media^{-1}$, 16.0 µg Ni kg $media^{-1}$, 43.9 µg Pb kg $media^{-1}$, and 200 µg Zn kg $media^{-1}$. The total export of metals was similar between SW and DI columns from the 0%, 20%, or 50% compost treatments, except for Cd (Figure 3). In general, SW did not increase total export of metals. The total export of metals was significantly higher from the 100% compost columns, and the SW100 exported significantly more metals compared to the DI100, except for Cu (Figure 3). The compost treatments retained more than 70% of the original SW inputs (Figure 4).

Xia et al. (2007) also found initial flushes of Cd, Cu, Pb, and Zn that were followed by a second flush over the leaching period, except for Cd and Pb, which continually declined. Peak metal concentration for SW and DI columns found in this experiment were lower than Xia et al. (2007) peak concentrations for compost and compost-soil blends. Mullane et al. (2015) leached a food yard-waste compost with a flow rate of 9.7 mL $minute^{-1}$ (5.5× the flow rate in this experiment) and found a similar Cu pulse followed by a rapid decline. Copper concentrations from our experiment were higher than they reported (107 vs. 80 $\mu g\ L^{-1}$), likely due to different compost sources.



347 **Figure 5.** Concentration of heavy metals in leachate from experimental columns during in pore

348 volume fractions. Six pore volumes of deionized water and simulated stormwater were leached at

349 a rate of 1.75 mL min^{-1} (1/10 pore volume of leachate collected every 10 minutes). Error bars

350 and letters of significance omitted for clarity.

The two pulses of metals are likely due to the behavior of the labile fraction of dissolved metals and DOM complexes leaving the system. The initial pulse in the leachate was from metal ions in the water filled pore space. The second peak was likely due to the formation of DOM complexes, from prolonged saturation, that leached from the columns. Dissolved organic matter readily forms complexes with metals, thereby accounting for the second flush of metals observed (Mullane et al., 2015; Xia et al., 2007; Hsu & Lo, 2001). Future studies should measure DOM to determine if increases in DOM correspond to increases in the metals. Metals showed similar patterns despite their differing chemical properties, suggesting that soil physical properties may play a critical role in regulating the distribution and mobility of these metals within the media (Hsu & Lo, 2001).

Implications and Limitations

There is evidence to suggest that compost-amended soils will export more nutrients and metals compared to unaltered and uncontaminated soil (Chahal et al., 2016; Mullane et al., 2015; Xia et al., 2007). However, the column experiment suggests the labile fraction of pollutants may be flushed from the compost within several pore volumes, especially for low sorption affinity species. The concentration of pollutants in the stormwater might affect longer-term export patterns such as metals that have higher retention (Pitt et al., 1999). The observed decline in pollutants depended on the constituent; NH_4^+ and Cd were rapidly exported compared to the slower release of NO_3^- and Cu (Figures 2 & 5). These results suggest leaching potential of compost are the highest in the first few storm events, and the media may equilibrate over time until the sorption sites are filled (Hunt et al., 2006; Clark and Pitt, 2009). This study used one source of compost, and those with different characteristics may behave differently. Additionally, it is recommended to choose a compost with a high P-sorption potential (Hatt et al., 2009; Hunt et al., 2006; McPhillips et al., 2018; Tirpak et al., 2021).

Conversely, the sorption experiment illustrated that the compost used can reduce the soil's ability to retain PO_4^{3-}. Compost rate also influenced heavy metal sorption capacity, which may in turn influence the storage and retention of these heavy metals by the soil. The lack of detection of heavy metals in the desorption measurements suggests that compost-soil blends can retain sorbed metals. Most LID practices use compost-soil blends (USEPA, 2016), and compost is typically mixed with soil at a rate of ≤ 50% by volume (Mohammadshirazi, et al., 2017; USEPA, 2016; Kranz et al., 2020). Compost rates ≤ 50% by volume may be acceptable to filter stormwater without adding to heavy metal loads. Furthermore, most compost sources contain pollutants, but at concentrations such that they will most likely not be hazardous to the environment (Forján et al., 2016; Paus et al., 2014).

The column retention experiment constituted a short-term scenario amounting to an equivalent of 22.8 cm of cumulative rainfall. The average rainfall in North Carolina in 2018 was 174 cm (NOAA, 2019); thus, this experiment represents 13% of the annual rainfall. Essentially, this was a hurricane-like event as 22.8 cm rainfall moved through the system within 10 hours, a 1 in 500 year storm event (Bonnin et al., 2006). Long-term monitoring is needed to determine when pollutant concentrations from compost-amended columns are reduced to a level where they are the same or less than the soil and when compost-amended column media sorption sites are full. Previous research in North Carolina has shown that nutrients and metals in runoff from compost-amended plots were substantially reduced after as few as three storm events (Rivers et al., 2021).

CONCLUSIONS

As compost becomes a more common component in stormwater management systems, it is important to know the potential impacts of compost on water quality. Ideally, systems will optimize infiltration and pollutant attenuation, but the high organic matter content of compost may lead to export of pollutants under certain hydrologic conditions. In this study, we analyzed sorption potential and pollutants exported through soil, compost-soil blends, and compost columns to assess how export behavior was affected by compost application rate. Our media sorption-desorption results suggest that compost may be a source of PO_4^{3-} and Cr, but other heavy metals might be highly retained on the compost-soil blends. Competitive sorption under field conditions may produce different results. Leaching of metals deep into the soil profile and uptake by plants may influence the storage and retention of metals. Strategic planting of plants known to uptake pollutants might help the compost-soil blend avoid long-term clogging and sorption saturation.

Our column export results suggest that incorporation of yard-waste compost in soil may cause an initial pulse of labile pollutants in effluent, but export may decline through time with successive storm events. Additionally, the amount of nutrients or metals exported from SW columns were similar to DI columns, except for NH_4^+ (20% compost) and Cd. The results of these two experiments suggest that yard-waste compost at $\leq$ 50% may be effective for retaining pollutants from stormwater without an increase in the net export of pollutants, until sorption sites are full. Future studies should consider different compost sources and soil types as they will have different competitive sorption.

CONFLICT OF INTEREST DISCLOSURE

The authors declare no competing financial interest.

AUTHOR CONTRIBUTIONS

Christina N Kranz: conceptualization, data curation, formal analysis, methodology, visualization, writing-original draft. **Erin N. Rivers:** conceptualization, data curation, formal analysis, methodology, visualization, writing-review & editing. **Joshua L. Heitman**: conceptualization, funding acquisition, methodology, supervision, project administration, writing-review & editing. **Richard A. McLaughlin**: supervision, project administration, writing-review & editing.

ACKNOWLEDGMENTS

This work was funded by the North Carolina Department of Transportation, project authorization number RP2019-06. We would like to thank Adam Howard, Dr. Aziz Amoozegar, and Dr. Wayne Robarge for their support in the lab.

SUPPLEMENTAL MATERIAL

This material details (1) soil and compost analysis methods, and (2) the experiment we conducted to determine an appropriate flow rate and number of pore volumes to use in experiment 1.

REFERENCES

Alshraah, S.H. (2020). Soil tillage for stormwater infiltration: Effects of amendments and vegetation type over time [Doctoral dissertation, North Carolina State University]. North Carolina State University Digital Repository. https://repository.lib.ncsu.edu/handle/1840.20/37396

Banks, M.K., Schwab, A.P., & Henderson, C. (2006). Leaching and reduction of chromium in soil as affected by soil organic content and plants. *Chemosphere*, 62, 255-264. https://doi.org/10.1016/j.chemosphere.2005.05.020.

Bonnin, M. et al., 2006. *Precipitation-frequency Atlas of the United States NOAA Atlas 14*, Volume 2, Version 3.0. NOAA National Weather Service, Silver Spring, MD.

Borchers, H.W. (2020). *pracma: Practical Numerical Math Functions.* https://cran.r-project.org/web/packages/pracma/index.html (accessed December 2020).

Boss, J., & Rix, A. (2020). *lodi: Limit of detection imputation for single-pollutant models*. https://cran.r-project.org/web/packages/lodi/lodi.pdf (accessed December 2020).

Brady, N.C., & Weil, R.R. (2010). *Elements of the nature and properties of soils*, 3rd ed., Upper Saddle River, NJ: Pearson Hall. Chahal, M.K., Shi, Z., & Flury, M. (2016). Nutrient leaching and copper speciation in compost-amended bioretention systems. *Science of the Total Environment, 556*, 302-309. https:doi.org/10.1016/j.scitotenv.2016.02.125

Choppala, G., Kunhikrishnan, A., Seshadri, B., Park, J.H., Bush, R., & Bolan, N. (2018). Competitive sorption of chromium species as influenced by pH, surface charge and organic matter content in contaminated soils. *Journal of Geochemical Exploration*, 184, 255-260. https://doi.org/10.1016/j.gexplo.2016.07.012.

Christensen, T.H. (1985). Cadmium soil sorption at low concentrations. IV. Effect of waste leachates on distribution coefficients. *Water, Air, and Soil Pollution,* 26, 265-274.

Clark, S., & Pitt, R. (2009). Storm-water filter media pollutant retention under aerobic versus anaerobic conditions. *Journal of Environmental Engineering*, 135(5), 367-371.

Crogger, C.G. (2005). Potential compost benefits for restoration of soils disturbed by urban development. *Compost Science & Utilization*, 13(4), 243-251.

Davis, A.P. (2005). Green engineering principles promote low-impact development. *Environmental Science and Technology, 39,* 338A-334A. https:doi.org/10.1021/es053327e

Davis, A.P. (2008). Field performance of bioretention: Hydrology impacts. *Journal of Hydrologic Engineering*, 13(2), 90-95. https:doi.org/ 10.1061/(ASCE)1084-0699(2008)13:2(90)

Davis, A.P., Hunt, W.F., Traver, R.G., & Clar, M. (2009). Bioretention Technology: Overview of current practice and future needs. *Environmental Engineering***,** 135(3), 109-117. https:doi.org/ 10.1061/(ASCE)0733-9372(2009)135:3(109)

Davis, A.P., Shokouhian, A., Sharma, H., Minami, C., & Winogradoff, D. (2003). Water quality improvement through bioretention: lead copper, and zinc removal. *Water and Environmental Resources*, 75, 73-75. https:doi.org/10.2175/106143003x140854

Davis, A.P. Shokouhian, M., Sharma, H., & Minami, C. (2006). Water quality improvement through bioretention media: Nitrogen and phosphorus removal. *Water Environment Research*, 78(3), 284-294. https:doi.org/10.2175/106143005X94376

Dietz, M.E. (2007). Low impact development practices: A review of current research and recommendations for future directions. *Water, Air, and Soil Pollution*, *186*, 351-363. https:doi.org/10.1007/s11270-007-9484-z

Dietz, M., & Clausen, J.C. (2006). Saturation to improve pollutant retention in a rain garden. *Environmental Science & Technology*, 40, 1335-1340. https:doi.org/10.1021/es051644f

Forján, R., Asensio, V., Rodríguez-Vila, A., & Covelo, E.F. (2016). Contributions of a compost-biochar mixture to the metal sorption capacity of a mine trailing. *Environmental Science and Pollution Research*, 23, 2595-2602. https:doi.org/10.1007/s11356-015-5489-0

Hatt, B.E., Fletcher, T.D., & Deletic, A., (2009). Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. *Journal of Hydrology*, 365, 310-321.

Hinman, C. (2009). *Bioretention soil mix review and recommendations for western Washington*. Washington State University. Pierce County Extention, Pullman, WA. http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=9D3D66D721A26FBCE87DAEFDD17C8020?doi=10.1.1.431.4124&rep=rep1&type=pdf

Horta, C. (2019). Fertilization with compost: effects on soil phosphorus sorption and on phosphorus availability in acid soils. *Open Journal of Soil Science*, 9, 255-268. https:doi.org/10.4236/ojss.2019.912016

Hsu, J. & Lo, S. (2001). Effect of composting on characterization and leaching of copper, manganese, and zinc from swine manure. *Environmental Pollution*, *14*, 119-127.

Hunt, W.F., Jarrett, A.R., Smith, J.T., & Sharkley, L.J. (2006). Evaluation bioretention hydrology and nutrient removal at three field sites in North Carolina. *Journal of Irrigation and Drainage Engineering*, 132, 600-608. https:doi.org/10.1061/(ASCE)0733-9437(2006)132:6(600)

Hurley, S., Shrestha, P., & Cording, A. (2017). Nutrient Leaching from compost: Implications for bioretention and other green stormwater infrastructures. *Journal of Sustainable Water Built Environment*, *3*, 04017006. https:doi.org/10.1061/JSWBAY.0000821

Jalali, M., & Jalili, A. (2011). Competitive adsorption of trace elements in calcareous soils as affected by sewage sludge, poultry manure, and municipal waste compost. *Environmental Earth Sciences*, 63, 731-739.

Kashem, M.A., & Singh, B.R. (2001). Metal availability in contaminated soils: I. Effects of flooding and organic matter on changes in Eh, pH and solubility of Cd, Ni and Zn. *Nutrient Cycling in Agroecosystems*, 61, 247-255.

Klimeski, A, Chardon, W.J., Turtola, E., & Uusitalo, R. (2012). Potential and limitations of phosphate retention media in water protection: A process-based review of laboratory and field-scale test. *Agricultural and Food Science*, 21, 206-223.

Kranz, C.N., McLaughlin, R.A., Johnson, A., Miller, G., Heitman, J.L. 2020. The effects of compost incprporation on soil physical properties in urban soils – A concise review. *Journal of Environmental Management*, 261, 110209.

Lair, G.J., Gerzabek, M.H., & Haberhauer, G. (2007). Sorption of heavy metals on organic and inorganic soil constituents. *Environmental Chemistry Letter*, 5, 23-27. https:doi.org/10.1007/s10311-06-0059-9

Li, H., & Davis, A.P. (2008). Heavy metal capture and accumulation in bioretention media. *Environmental Science & Technology*, 42, 5247-5253. https:doi.org/10.1021/es702681j

Li, Y.C., Stoffella, P.J., Alva, A.K., Calvert, D.V., & Graetz, D.A. (2013). Leaching of nitrate, ammonium, and phosphate from compost amended soil columns. *Compost Science and Utilization*, 5(2), 63-67. https:doi.org/10.1080/1065657X.1997.10701875

Line, D.E., Brown, R.A., Hunt, W.F., & Lord, W.G. (2012). Effectiveness of LID for commercial development in North Carolina. *Journal of Environmental Engineering*, 138, 680–688. https:doi.org/10.1061/(ASCE)EE.1943-7870.0000515

Macnamara, J. & Derry, C. (2017). Pollution removal performance of laboratory simulations of Sydney's street stormwater biofilters. *Water*, 9 (11), 907. https:doi.org/10.3390/w9110907

Maestre, A., & Pit, R. (2005). National stormwater quality database, version 1.1: A compilation and analysis of NPDES stormwater monitoring information. *U.S. EPA Office of Water*, Washington D.C. http://rpitt.eng.ua.edu/Publications/Stormwater%20Characteristics/NSQD%20EPA.pdf

Mahler, R.L. (2004). *Nutrients plans require for growth*. University of Idaho Extension. https://www.extension.uidaho.edu/publishing/pdf/CIS/CIS1124.pdf

McLaughlin, R.A, Kang, J., & Wiseman, J. (2013). *Sediment basin design criteria for flocculated sediment.* North Carolina Department of Transportation (Project authorization number 2011-15). https://connect.ncdot.gov/projects/research/RNAProjDocs/2011-15FinalReport.pdf

McLaughlin, R.A., & Knappe, D. (2018). *Optimal factors of sediment flocculation in construction site runoff*. North Carolina Department of transportation (Project authorization number 2015-16). https://connect.ncdot.gov/projects/research/RNAProjDocs/2015-16%20Final%20Report.pdf

McPhillips, L., Goodale, C., & Walter, M.T. (2018). Nutrient leaching and greenhouse gas emissions in grassed detention and bioretention stormwater basins. *Journal of Sustainable Water in the Build Environment*, 4(1), 04017014.

Mohammadshirazi, F., McLaughlin, R.A., Heitman, J.L., & Brown, V.K. (2017). A multi-year study of tillage and amendment effects on compacted soils. *Journal of Environmental Management, 203*, 533-541. https:doi.org/10.1016/jenvman.2017.07.031

Mullane, J.M., Flury, M., Iqbal, H., Freeze, P.M., & Hinman, C. (2015). Intermittent rainstorm causes pulses of nitrogen, phosphorus, and copper in leachate from compost in bioretention systems. *Science of the Total Environment, 537*, 294-303. https:doi.org/10.1016/j.scitotenv.2015.07.157

NCDEQ. (2018). *North Carolina Stormwater Control Measure Credit Document*. North Carolina Department of Environmental Quality. https://files.nc.gov/ncdeq/Energy%20Mineral%20and%20Land%20Resources/Stormwater/BMP%20Manual/SCM-Credit-Doc-2018-11-7.pdf

NCDOT. (2014). *Stormwater best management practices toolbox*. North Carolina Department of Transportation.

NOAA National Centers for Environmental Information. (2019). *State Climate Summaries: North Carolina*. https://statesummaries.ncics.org/chapter/nc/#:~:text=Statewide%20average%20annual%20precipitation%20has,of%2068.4%20inches%20in%202018

OECD. (2000). *Test No. 106: Adsorption -- Desorption Using a Batch Equilibrium Method,* OECD Guidelines for the Testing of Chemicals, Section 1, OECD Publishing, Paris. https:doi.org/10.1787/9789264069602-en

Paus, K.H., Morgan, J., Gulliver, J.S., & Hozalski, R.M. (2014). Effects of bioretention media compost volume fraction on toxic metals removal, hydraulic conductivity, and phosphorous release. *Journal of Environmental Engineering*, 140(10), 04014033. https: doi.org/10.1061/(ASCE)EE.1943-7870.0000846

Pitt, R., Lantrip, J., Harrison, R., Henry, C.L., & Xue, D. (1999). *Infiltration through Disturbed Urban Soils and Compost-Amended Soil Effects on Runoff Quality and Quantity* (USEPA Report 600/R-00/016, NTIS PB2000-102012). Washington, DC: U.S. Government Printing Office.

R Core Team. (2021). *R: A Language and Environment for Statistical Computing.* R Foundation for Statistical Computing: Vienna, Austria.

Rice, E.W., Baird, R.B., Eaton, A.D., & Clesceri, L.S. (2012). *Standard methods for the examination of water and wastewater* (pp 541). American Public Health Association. Washington, DC: U.S. Government Printing Office.

Rivers, E.N., Heitman, J.L., McLaughlin, R.A., & Howard, A.M. (2021). Reducing roadside runoff: Tillage and compost improve stormwater mitigation in urban soils. *Journal of Environmental Management*, 280, 111732. https:doi.org/10.1016/j.jenvman.2020.111732

Ramos, S.J., Pinto, D.A., Guedes, R.S., Dias, Y.N., Caldeira, C.F., Gastauer, M., Souza-Filho, P.W., & Fernandes, A.R. (2021). Açaí biochar and compost affect the phosphorus sorption, nutrient availability, and growth of *Dioclea apurensis* in iron mining soil. *Minerals*, 11,0. https://doi.org/10.3390/min11060000

Sauvé, S., Hendershot, W., & Allen, H. (2000). Solid-solution partitioning of metals in contaminated soils: Dependence on pH, total metal burden, and organic matter. *Environmental Science and Technology*, 34, 1125-1131.

Subramaniam, D., Matherm P., Russell, S., & Rajapakse, J. (2015). Dynamics of nitrate-nitrogen removal in experimental stormwater biofilters under intermittent wetting and drying. *Journal of*

Environmental Engineering, 143 (3), 04015090. https:doi.org/10.1061/(ASCE)EE.1943-7870.0001043

Tirpak, R., Nabiul Afrooz, ARM, Winston, R.J., Valenca, R., Schiff, K., & Mohanty, S.K. (2021). Conventional and amended bioretention soil media for targeted pollutant treatment: A critical review to guide the state of practice. *Water Research*, 189, 116648. https:doi.org/10.1016/j.watres.2020.116648

Weiss, J., Hondzo, N., Biesboer, D., & Semmesns, N. (2006). Laboratory study of heavy metal phytoremediation by three wetland macrophytes. *International Journal of Phytoremediation*, 8, 245-259. https:doi.org/10.1080/15226510600846798

Wilson, C.E., Hunt, W.F., Winston, R.J., & Smith, P. (2015). Comparison of runoff quality and quantity from a commercial low-impact and conventional development in Raleigh, North Carolina. *Journal of Environmental Engineering*, 141, 05014005. https:doi.org/10.1061/(ASCE)EE.1943-7870.0000842

Xia, Y.P., He, Z.L., Stoffella, P.J., Calvert, D.V., Zhang, M.K., Yang, X.E., & Wilson, S.B. (2005). Effect of compost amendment on heavy metal, nitrogen and phosphorus in a peat-based container medium. *Pedosphere*, 15(6):792-796.

Xia, Y.P., Stoffella, P.J., He, Z.L., Zhang, M.K., Calvert, D.V., Yang, X.E., & Wilson, S.B. (2007). Leaching Potential of heavy metals, nitrogen, and phosphate from compost-amended media. *Compost science and Utilization, 15*, 29-33.

Xu, T., Nan, F., Jiang, X., Tang, Y., Zeng, Y., Zhang, W., & Shi, B. (2020). Effect of soil pH on the transport, fractionation, and oxidation of chromium (III). *Ecotoxicology and Environmental Safety*, 195, 110459. https://doi.org/10.1016/j.ecoenv.2020.110459

water

MDPI

Article

Characterizing Compost Rate Effects on Stormwater Runoff and Vegetation Establishment

Christina N. Kranz , Richard A. McLaughlin and Joshua L. Heitman *

Department of Crop and Soil Sciences, North Carolina State University, Raleigh, NC 27607, USA; cnkranz@ncsu.edu (C.N.K.); rich_mclaughlin@ncsu.edu (R.A.M.)
* Correspondence: josh_heitman@ncsu.edu

Abstract: Urban development exposes and compacts the subsoil, resulting in reduced infiltration, which often leads to problems with establishing vegetation, increased erosion, and increased runoff volumes. Compost incorporation into these soils can potentially enhance soil physical properties, vegetation establishment, and pollutant removal. The goal of this field study was to determine the efficacy of compost as a soil improvement measure to reduce runoff volume, improve runoff quality, and increase vegetation establishment on a disturbed sandy clay subsoil representing post-development conditions. Two sources of compost were tested: (1) a certified yard waste product at 10%, 30%, and 50% by volume, and (2) an uncertified yard waste product at 30% by volume, both compared to a tilled, no-compost control. Treatment plots were established at Lake Wheeler Road Field Laboratory in Raleigh, NC, and observed for one year. Tilling alone may have been sufficient to reduce runoff quantity as few differences were found between tilled and compost amended plots. Runoff water quality also did not differ according to compost addition. However, the certified compost increased biomass production proportionally to the amount added and compared to the uncertified compost at the same rate. The improved vegetation establishment with compost is important for long-term erosion control and ecosystem services. The results of this study suggest (1) tilling is a viable option to achieve high infiltration rates and reduce runoff volumes, (2) compost incorporation does not reduce nor improve water quality, and (3) compost may yield more robust vegetation establishment.

Keywords: stormwater; compost; urban soils; infiltration rate; compacted

Citation: Kranz, C.N.; McLaughlin, R.A.; Heitman, J.L. Characterizing Compost Rate Effects on Stormwater Runoff and Vegetation Establishment. *Water* **2022**, *14*, 696. https://doi.org/10.3390/w14050696

Academic Editors: Peter Weiss and Ryan Winston

Received: 24 January 2022
Accepted: 18 February 2022
Published: 23 February 2022

1. Introduction

Urban development can result in highly disturbed areas in which soil is severely compacted [1,2]. Soil can be compacted intentionally to increase soil strength or unintentionally from heavy equipment traffic. Topsoil is often removed during the construction process resulting in a nutrient poor subsoil exposed at the soil surface. Thus, development affects both soil physical properties and vegetation establishment [3,4]. Many studies have reported that compacted soils have reduced porosity [5–7], infiltration rate [8–11], and vegetation establishment [11–13], which, in turn, leads to increased runoff and erosion [3,14]. Runoff from compacted soils are often directed into overloaded stormwater systems and streams channels [14].

Establishing vegetation helps to create pathways in the soil for infiltration, which is necessary for erosion and sediment control [4,11,15]. One method of improving the soil environment is to till or incorporate compost into the compacted subsoils. Incorporating compost can increase the porosity and infiltration rate, while compost additionally provides essential plant nutrients to the nutrient-depleted subsoil [3,4]. Compost can also remove pollutants from the infiltrating stormwater, resulting in cleaner runoff [16,17]. These beneficial effects are interactive and are attributed to the amount of compost applied and the amount of organic matter (OM) in the compost feedstock.

The hydrological response to compost incorporation in compacted soils has been variable, with compost incorporation increasing infiltration at some sites while tilling without adding compost was sufficient to improve infiltration at others [10,11,18,19]. Logsdon et al. [10] observed that compost incorporation improved infiltration compared to a no compost control and a compost blanket up to four years after compost application. Conversely, Mohammadshirazi et al. [11] found that compost incorporation and tilling the soil resulted in the same infiltration two years after compost application. However, both compost incorporation and tilling increased infiltration compared to a compacted soil with no compost. Many studies on compost incorporation have only examined one compost application rate and one source of compost [8–11,18,20]. The addition of compost to soils may have a range of effects on soil function due to the complexity of the soil's and compost's physical, chemical, and biological properties [19,20].

In addition to providing essential plant nutrients, compost can also be a source of nutrients and metals in runoff, depending on hydrologic conditions, the compost feedstock, and the compost maturity [21–23]. When compost is used on roadsides to filter stormwater, there is the potential for compost to alter the nutrient and metal export concentration and patterns. As compost incorporation in degraded urban soils becomes an increasingly popular approach for soil improvement, it is important to understand how compost incorporation and stormwater interact, so it can be used as an effective stormwater control measure (SCM).

The purpose of this study was to determine the potential of compost incorporation to reduce runoff volume, improve runoff quality for ecological reasons, and increase vegetation establishment in a sandy clay soil over the course of a growing season. Compost incorporation at rates of 0%, 10%, 30%, and 50% compost by volume, and including two sources of compost, were tested at field scale in the Piedmont region of North Carolina, USA. Runoff was sampled after each natural storm event. Specifically, we determined whether compost incorporation would (1) change runoff volume or infiltration rate (IR) compared to a tilled control, (2) alter dissolved pollutant concentrations and export patterns in runoff, and (3) change biomass production. We hypothesized that compost incorporation will improve soil physical properties and increase vegetation establishment, resulting in increased IR, reduced runoff volumes, reduced sediment loads, and reduced pollutant transport. We additionally hypothesized that, as the rate of compost application increases, there will be further improvements to the three parameters mentioned above.

2. Materials and Methods

2.1. Site Description and Treatments

The field study was conducted at the Lake Wheeler Road Field Laboratory, Raleigh, NC, USA, in the Piedmont region of North Carolina. Plots were established in May of 2020. The site was located on a grassed slope mapped as Cecil (fine, kaolinitic, thermic Typic Kanhapludults) [24]. The site was intended to mimic post-development soil conditions (e.g., along a roadside) within the region; the Cecil soil series is mapped on approximately 2.3 million hectares within the southeastern USA. The topsoil and vegetation were removed to expose the subsoil, and the area was graded to achieve a uniform surface with a slope of 5% to allow for some surface drainage. The subsoil was then tilled to approximately 15 cm depth using a rotary tiller. Each plot received fertilizer at a rate of 560 kg ha^{-1} and lime at a rate of 4483 kg ha^{-1}. Fertilizer was a 10-20-20 blend of nitrogen (total nitrogen), phosphate (P_2O_5), and potassium (K_2O), respectively, according to North Carolina Department of Transportation (NCDOT) guidelines for grass establishment [25]. Fertilizer and lime were mixed in during tillage. Particle size analysis was performed on the exposed subsoil using the hydrometer method [26] from composite samples (0–15 cm depth). The subsoil contained 52% sand, 12% silt, and 36% clay (sandy clay texture).

Plots were set up in a completely randomized block design, where each of the five treatments were replicated once in each of the four blocks. Individual plots were delineated with wooden boards (1.5 m wide by 3.0 m long by 0.3 m tall) with an isosceles triangle

(0.7 m length of each wooden board) on the down slope end of the plot in order to funnel water to a collection point. Wooden boards were inserted about 5 cm into the soil (Figure 1). A PVC pipe was attached between the two equal sides of the triangle to direct runoff to a 114 L plastic tub. The edges and gaps were sealed with expanding foam (Great Stuff, Dow Chemical Company, Wilmington, IL, USA). Each tub was fitted with a lid to prevent direct precipitation inputs.

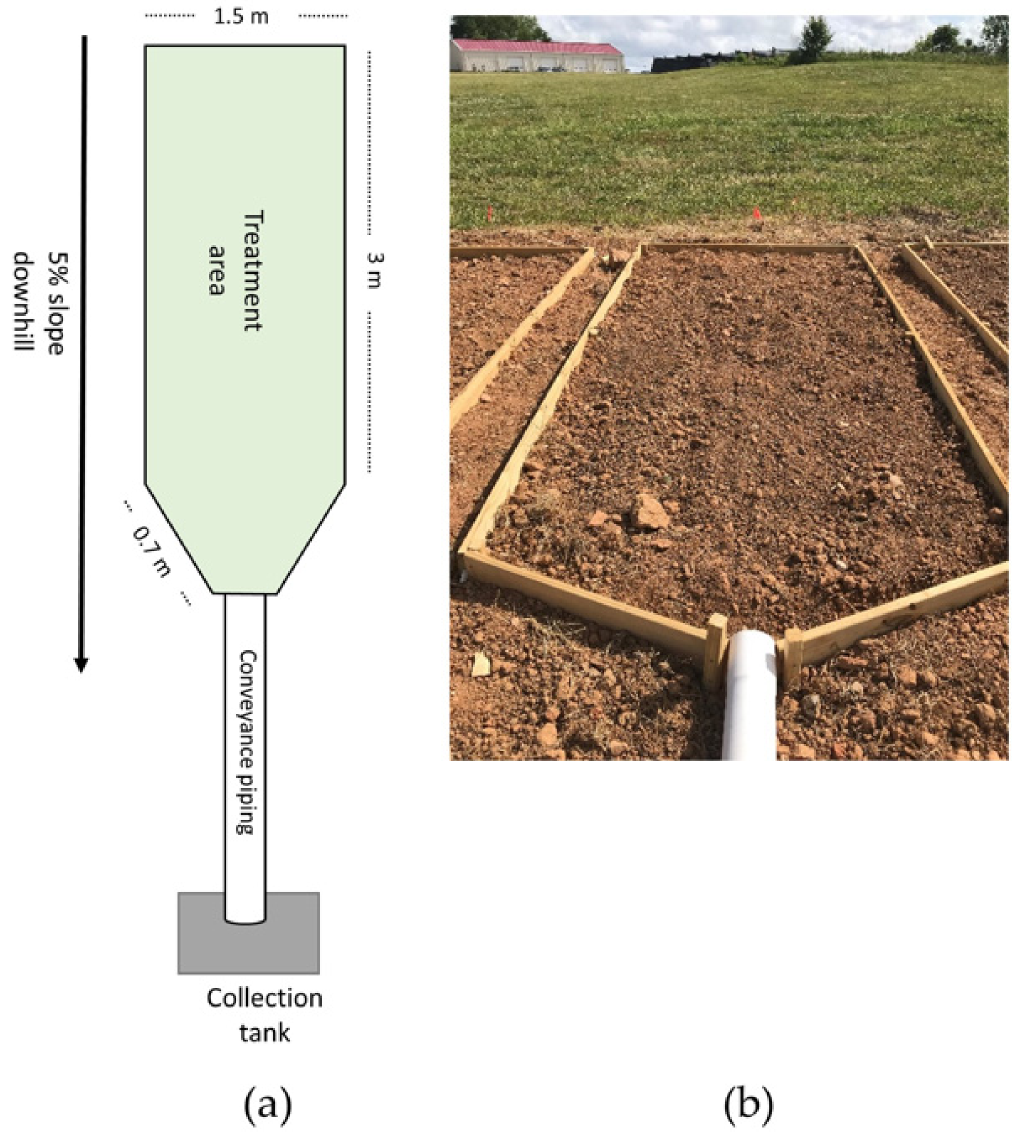


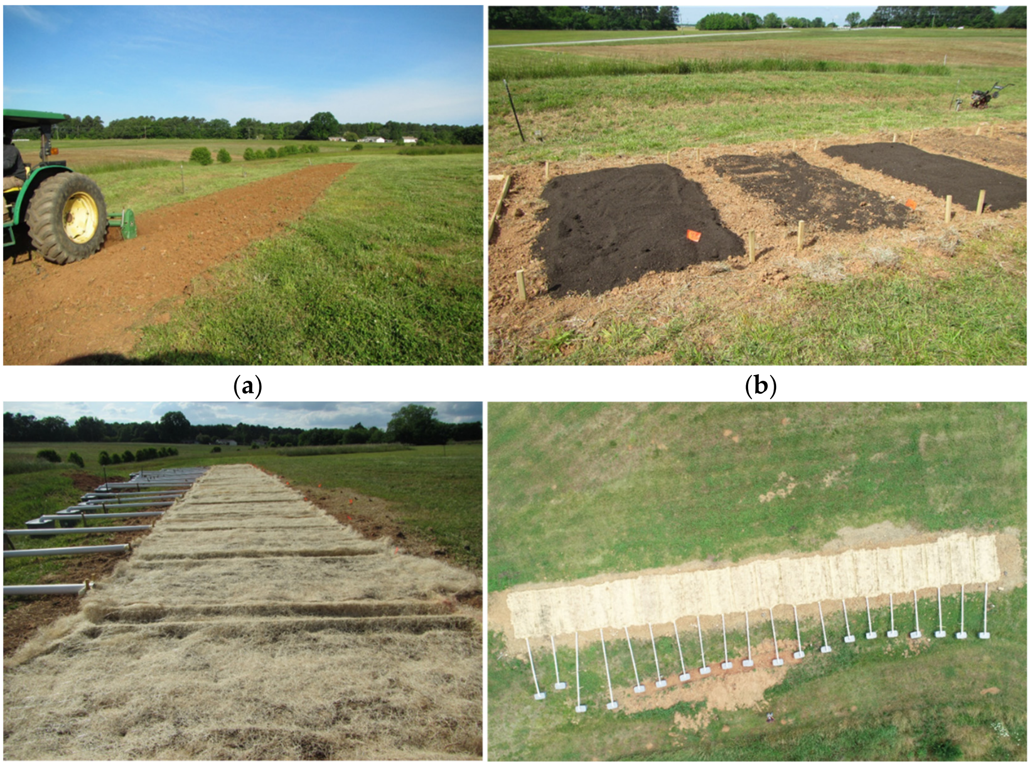
Figure 1. (**a**) Top view of site configuration showing connection between plot area and collection tank; (**b**) Plan view of site configuration before treatment application looking upslope.

Compost was sourced from two manufactures: (1) McGill SportsTurf ® (New Hill, NC, USA) and (2) North Carolina State University (Raleigh, NC, USA). These compost sources were used to make soil–compost blends. The McGill compost was a blend of woody materials, yard waste, agricultural by-products, and food waste and is a Seal of Testing Assured (STA) certified compost by the US Composting Council. The North Carolina State University compost was a blend of woody materials, yard waste, and food waste and is uncertified. Yard waste can include leaves, plants, straw, and woody debris. A basic nutrient analysis of the soil and compost was conducted by Brookside Laboratories, Inc. (New Breman, OH, USA) (Table 1).

Table 1. Nutrient analysis of certified compost, uncertified compost, and the subsoil.

Property	Certified Compost	Uncertified Compost	Subsoil
Organic Matter (%)	26.7	79.7	1.6
Carbon (%)	17.7	30.4	0.7
Total Nitrogen (%)	1.45	1.64	0.06
C/N Ratio	12.2	18.5	11.7
Total Phosphorus (%)	0.32	0.19	0.07
Total Potassium (%)	0.37	0.48	0.16
pH	6.7	6.3	4.4

Compost was tilled into the top 15 cm of the soil. The McGill compost (certified compost) was incorporated at 10% (C10), 30% (C30), and 50% (C50) compost by volume. The North Carolina State University compost (uncertified compost) was incorporated at 30% (U30) compost by volume. There was also a tilled only control (0% compost). The compost rates were chosen because they are representative of a low, medium, and high compost rate observed in the literature [3,4]. All plots were seeded with a NCDOT seeding mix including tall fescue (*Festuca arundinacea*) at 84 kg ha^{-1} and hulled bermudagrass (*Cynodon dactylon*) at 28 kg ha^{-1} [25]. A single-net erosion control blanket (excelsior matting) was used to cover the plots after seeding and anchored with metal sod staples (Figure 2). Plots were re-seeded with the same seed mix and rates as above six months after site establishment to improve stand density.



(**a**) (**b**) (**c**) (**d**)

Figure 2. Site preparation evolution: (**a**) tilling treatment area; (**b**) compost addition to plots. From left to right: 50%, 10%, and 30% compost by volume; (**c**) side view of finished site preparation; (**d**) top view of finished site preparation.

2.2. Runoff Qualtity and Quality

Rainfall data were collected from a HOBO RX3000 Weather Station (Bourne, MA, USA) located 5 m from the plots. After each rain event, the runoff volumes were determined by recording the depths of water in the collection tubs for each plot and calculating the volumes from a calibration curve. Water within the tubs was mixed thoroughly to suspend sediments while 1 L subsamples were taken. These subsamples were analyzed for total suspended solids (TSS) and turbidity. Additionally, the first three storm events were analyzed for dissolved nutrients (ammonium [NH_4^+], nitrate [NO_3^-], and phosphate [PO_4^{-3}]) and heavy metals (copper [Cu], lead [Pb], and zinc [Zn]). The TSS was determined by filtration [27] using 90 mm glass fiber filters (ProWeight, Environmental Express, Mt. Pleasant, SC, USA). Turbidity was measured using a nephelometer (McVan Instruments, Victoria, Australia) according to the USEPA standard method 180.1 [28]. Nutrients were analyzed on a Lachat Quikchem® 8500 (Milwaukee, WI, USA), and heavy metals were analyzed on Perkin Elmer Elan DRCII inductively coupled plasma-mass spectrometer (Waltham, MA, USA) using standard methods [29]. Nutrient and heavy metal export was calculated from:

$$\text{export} = \text{runoff volume} \times \text{concentration} \tag{1}$$

and scaled up to grams per hectare.

2.3. Vegetation Establishment

Grass biomass samples were collected, and mowing occurred 51 (Event 1), 71 (Event 2), 96 (Event 3), and 138 (Event 4) days after plots were established. Clippings from two randomly selected 20 × 50 cm rectangles were cut to 10 cm above the ground in accordance with NCDOT mowing guidelines [25]. Samples were placed in paper bags, dried at 65 °C for 48 h, and then weighed to determine above ground biomass. Individual plot biomass was estimated from the average of the two samples. Plots were mowed to 10 cm above the ground as recommended by the NCDOT [25].

2.4. Infiltration Rate and Bulk Density

Bulk density and IR measurements were taken 11 months after plot establishment in April 2021, and two samples were taken or measured per plot. Bulk density samples from the upper 10 cm of the soil were taken using a 6 cm diameter core sampler (AMS Inc., American Falls, ID, USA). The top 2.5 cm ring from each sample was discarded to avoid measuring any minor compaction caused by the sampler's hammer driver. Bulk density samples were weighed, oven dried at 105 °C, and re-weighed to determine the water content and bulk density.

The constant head single-ring infiltrometer method was used to measure IR [30] with an 11 cm diameter ring inserted to a depth of 7.5 cm. A thin layer of gravel was placed on the soil surface to prevent altering the soil surface at the start of the infiltration process. A pressure head of 5 cm was established at the soil surface, and the rate of water flow from an attached supply reservoir was recorded over time intervals until three constant, consecutive readings were achieved, which typically took about 30 min. The IR was calculated from these data using the Reynolds and Elrick method [31].

2.5. Statistical Analysis

All statistical analyses were performed in R version 4.0.4 [32]. Storm events 9, 12, and 20, resulting from Hurricanes Isaias (152.4 mm rainfall), Kyle (147.0 mm rainfall), and Zeta (122.4 mm rainfall), respectively, were removed from the data set due to runoff collection bins overflowing. A linear mixed effect model was used to account for the special and temporal correlation resulting from the study design. Treatment was a fixed effect and plot within block as a random variable in order to account for differences among treatment blocks [33]. A one-way analysis of variance (ANOVA) with Tukey' HSD pairwise comparison (α= 0.05) was used to evaluate differences between treatments for runoff, IR, bulk density, water content, TSS, turbidity, nutrient loads, and heavy metal loads. For biomass, the data were not transformed, and the data were found to be described by a polynomial function. A one-way ANOVA was used to determine if there was any variation in biomass production by treatment (Tukey' HSD test, α= 0.05).

3. Results

3.1. Runoff Quantity

There were 23 storm events during the May 2020 to December 2020 observation period. Three of these storm events (9, 12, and 20) were removed; thus, 20 storm events were analyzed. Mean rainfall per storm event during the collection period was 57 mm (ranging from 39–82 mm), and mean rainfall intensity per storm event was 55 mm h^{-1} (ranging from 30–137 mm h^{-1}). Across all treatment plots, runoff was significantly correlated with total rainfall ($p < 0.01$) and rainfall intensity ($p < 0.05$). The ANOVA showed there were no differences between treatments for each individual storm event (Figure 3). All treatments resulted in very low runoff (<10%) relative to rainfall for the 20 cumulative storm events.

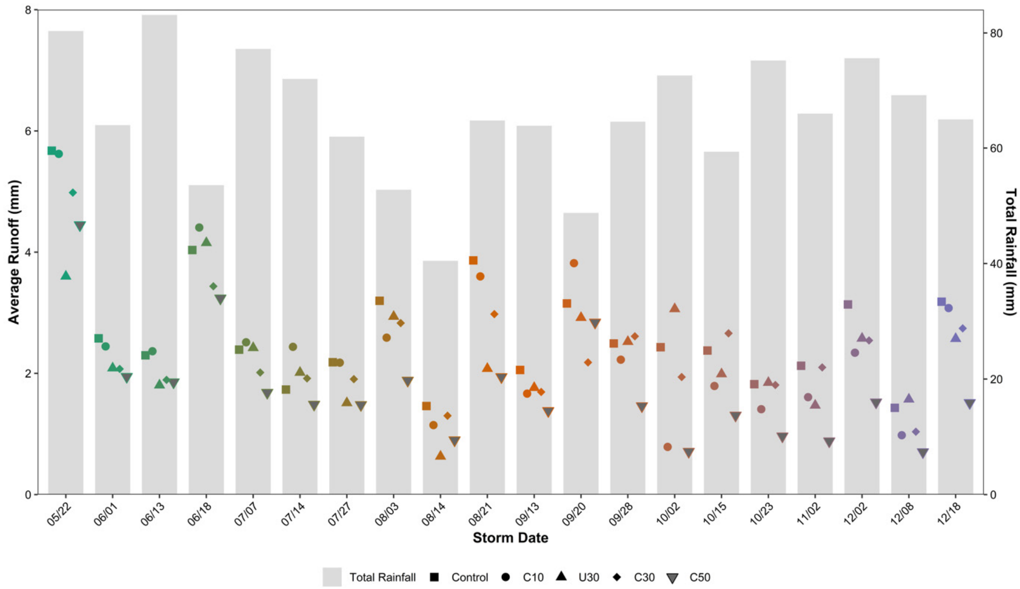


Figure 3. The symbols indicate the average runoff for each treatment from storm dates (mm/dd). The grey bars indicate the rainfall that occurred from each storm. Control: no compost. C10: 10% certified compost. U30: 30% uncertified compost. C30: 30% certified compost. C50: 50% certified compost.

3.2. Runoff Water Quality

All storm event runoff water was analyzed for TSS and turbidity, and the first three storm events were analyzed for dissolved nutrients and heavy metals. There were no significant differences in turbidity, with an average value of 21 NTU (Figure 4). For TSS, one storm event, 7 July (Storm Event 5), resulted in significant differences, while no differences were found on any other storm dates (Figure 4). The U30 runoff resulted in higher TSS compared to the control, but the U30 was not different from the certified compost treatments. The TSS for storm events were significantly correlated with total rainfall ($p < 0.05$) and rainfall intensity ($p < 0.001$). In this study, the use of compost, up to 50% by volume, did not increase nor decrease the turbidity or TSS in runoff compared to the control.

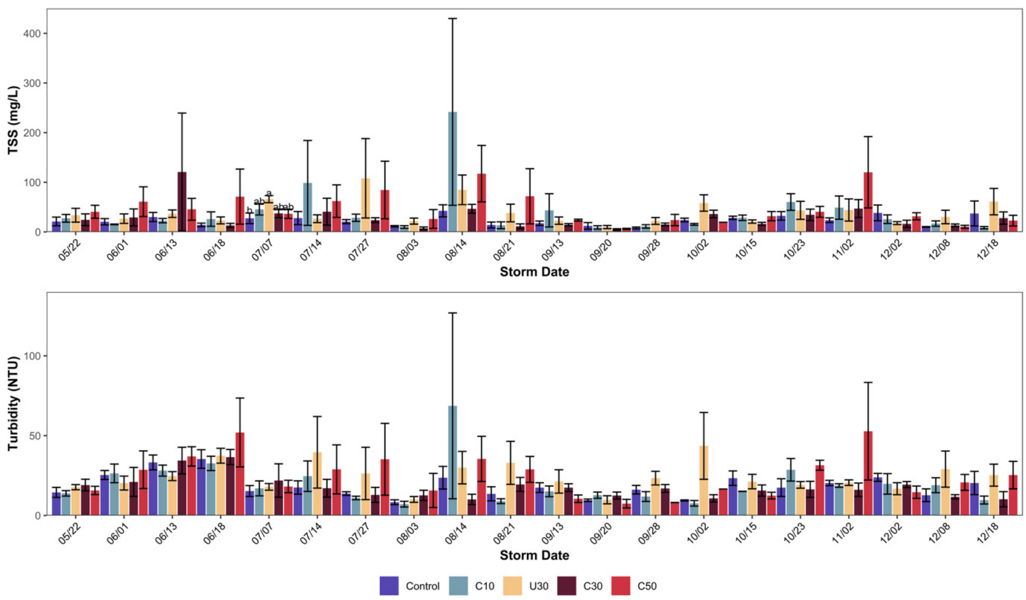


Figure 4. (**top**) Total suspended solids (TSS); (**bottom**) turbidity from runoff samples by storm date (mm/dd). Error bars ± 1SE, $n = 4$. Letters indicate significant differences between treatments by date (Tukey's HSD Test, $p < 0.05$).

Patterns in dissolved nutrients and heavy metals were variable across storm events and among treatments. However, treatments followed relatively similar export patterns during each storm event. There were no differences in PO_4^{3-} for any of the three storm events measured (Figure 5). There was a trend of increasing PO_4^{3-} export with each storm event. There were no differences in NH_4^+ export. Nitrate export was relatively the same for all three storms, except the C30 treatment that produced highly variable export for Storm Event 3 (13 June). Nitrate was the only nutrient to have significant differences, and this was for Storm Event 3. The U30 runoff resulted in higher ($p < 0.01$) NO_3^- export (140 g ha^{-1}) compared to all other treatments, which were less than 50 g ha^{-1} (Figure 5).

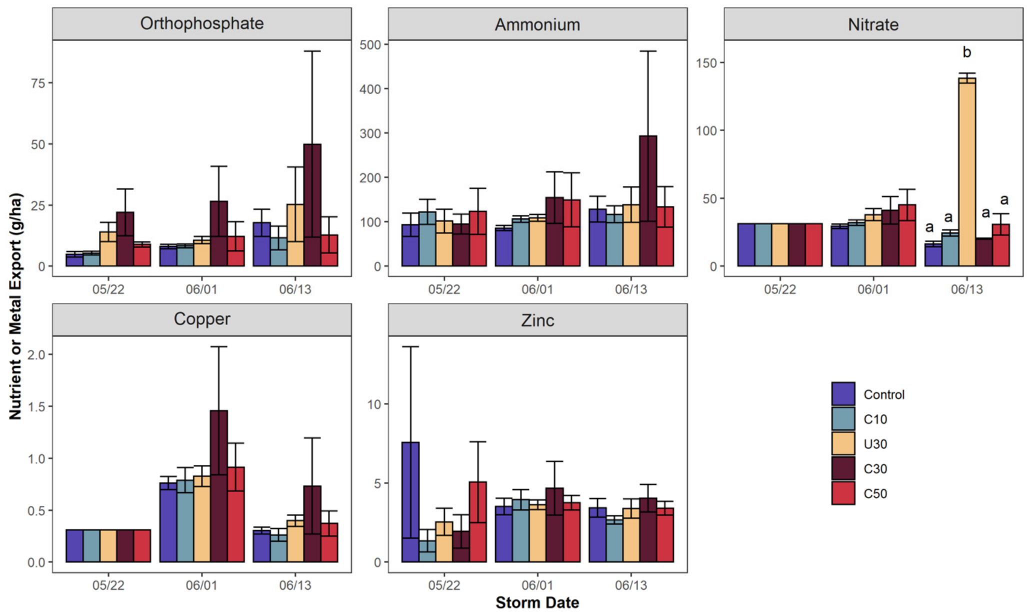


Figure 5. Nutrient and heavy metal export from plots for the first three storms. Error bars ± 1SE, $n = 4$. Letters indicate significant differences between treatments by date (Tukey's HSD Test, $p < 0.05$).

There were no differences in heavy metal export (Figure 5). Lead was below detection for all treatments and storm events (<4.2 μg L^{-1}). Peak export of Cu was reported from Storm Event 2, and then decreased for the following storm event to values near Storm Event 1. The highest reported export value for Cu was the C30 treatment at Storm Event 2 (1 g ha^{-1}) (Figure 5). The C30 treatment appears to produce the most variation as it did with PO_4^{3-} and NH_4^+ export. Copper concentrations ranged from below detection to 2.0 μg L^{-1} (Table 2). Zinc had variable export for Storm Event 1 but appears to have steady export with the three measured storm events (Figure 5). The maximum Zn export was the control on Storm Event 1 at 7 g ha^{-1}. Zinc concentrations ranged from 3.0 to 27.2 μg L^{-1} (Table 2).

Table 2. Water quality constituents (±SE) in runoff from control, certified 10% compost (C10), uncertified 30% compost (U30), certified 30% compost (C30), and certified 50% compost (C50) in plots during sampled storm events. All compost is percent by volume. N.D. is no detection. Detection limit was <0.1 mg L^{-1} for dissolved nutrients and <1.0 μg L^{-1} for dissolved metals. $n = 4$. Letters indicate significant differences between treatments (Tukey's HSD Test, $p < 0.05$).

	PO_4^{3-}	NO_3^-	NH_4^+	Zn	Cu
		mg L^{-1}		ug L^{-1}	
Event 1: 22 May					
Control	0.011 (0.002)	N.D.	0.212 (0.06)	17.040 (0.014)	N.D.
C10	0.012 (0.001)	N.D.	0.278 (0.065)	3.030 (0.000)	N.D.
U30	0.032 (0.001)	N.D.	0.231 (0.061)	6.730 (0.002)	N.D.
C30	0.050 (0.022)	N.D.	0.216 (0.052)	4.800 (0.002)	N.D.
C50	0.020 (0.002)	N.D.	0.280 (0.119)	11.990 (0.006)	N.D.
Event 2: 1 June					
Control	0.046 (0.005)	0.167 (0.009)	0.488 (0.032)	20.610 (0.002)	4.350 (0.0357)
C10	0.047 (0.004)	0.182 (0.011)	0.606 (0.042)	26.057 (0.004)	4.500 (0.692)
U30	0.061 (0.009)	0.216 (0.026)	0.620 (0.038)	21.720 (0.002)	4.725 (0.562)
C30	0.151 (0.082)	0.235 (0.059)	0.883 (0.332)	27.240 (0.010)	8.325 (3.517)
C50	0.067 (0.034)	0.257 (0.066)	0.853 (0.349)	21.970 (0.003)	5.225 (1.321)
Event 3: 13 June					
Control	0.117 (0.037)	0.107 (0.013) a	0.846 (0.193)	27.057 (0.003)	2.000 (0.227)
C10	0.076 (0.032)	0.160 (0.015) a	0.770 (0.126)	16.380 (0.002)	1.727 (0.407)
U30	0.167 (0.100)	0.181 (0.024) b	0.913 (0.229)	22.057 (0.004)	2.625 (0.359)
C30	0.329 (0.252)	0.133 (0.003) a	1.933 (1.267)	26.550 (0.006)	4.827 (3.051)
C50	0.084 (0.047)	0.203 (0.051) a	0.879 (0.301)	22.480 (0.003)	2.450 (0.798)

3.3. Vegetation Establishment

Biomass was collected four times during the field study, 51, 71, 96, and 138 days after plot establishment. At Day 51 (Event 1), the C50 treatment resulted in higher ($p < 0.05$) biomass compared to the control, U30, and C10 treatments, but was the same as C30 treatment (Figure 6). At Days 71 and 96 (Events 2 and 3), all certified compost treatments (C10, C30, C50) produced more ($p < 0.05$) biomass than the control and U30 treatment. By Day 138 (Event 4), the control resulted in lower biomass ($p < 0.05$) than the C30 treatment, but all other treatments were considered the same. Day 138 also had the most variation in biomass for U30, C30, and C50 treatments. This may be attributed to cooler fall temperatures and the volunteer vegetation (annual ryegrass) dying off in the treatment plots. For the cumulative biomass from all four sampling dates, the C50 treatment generated significantly more biomass followed by the C30, C10, control, and U30 treatments, respectively (Table 3). The certified compost resulted in greater biomass production compared to the uncertified compost. The C50 treatment produced more than double the biomass compared to the control and U30.

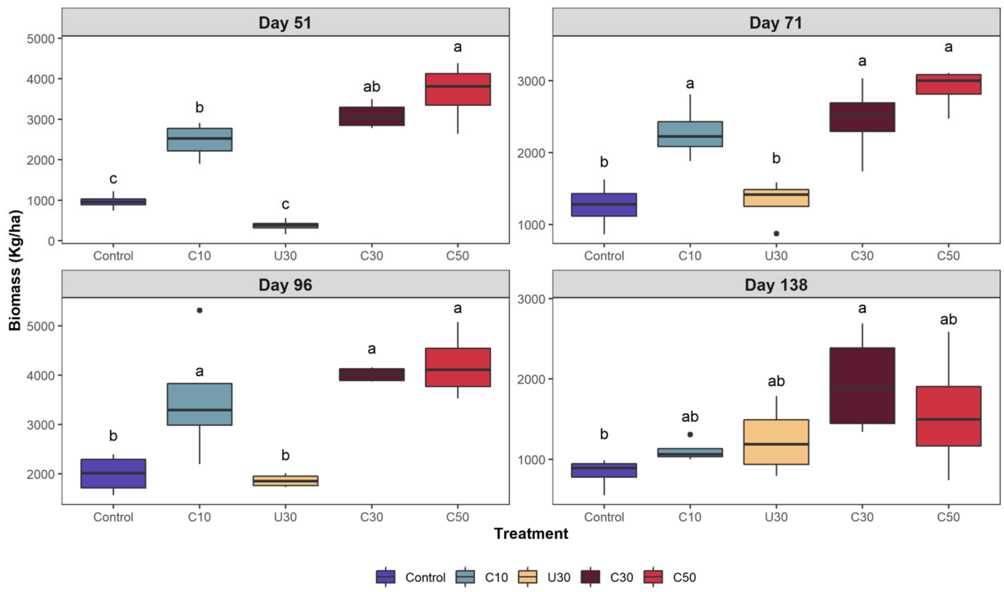


Figure 6. Average biomass (cut 10 cm above the soil) for treatments by days after seeding (51, 71, 96, and 138 days, respectively). Error bars ± 1SE, n = 8. Letters indicate significant differences between treatments by event (Tukey's HSD Test, $p < 0.05$).

Table 3. Total biomass from all four sample dates (±SE), n = 16, and water content (±SE), bulk density (±SE), and infiltration rate (IR) (±SE) of treatment plots 11 months after establishment, n = 8. Letters indicate significant differences between treatments (Tukey's HSD Test, $p < 0.05$).

Treatment	Total Biomass (kg ha^{-1})	Water Content (%)	Bulk Density (g cm^{-3})	IR (cm h^{-1})
Control	20,241 (247) d	10.2 (0.3) b	1.35 (0.03) a	27.3 (4.2) c
C10	37,522 (507) c	16.0 (3.8) a	1.19 (0.04) b	36.0 (2.7) b
U30	19,175 (284) d	16.3 (0.9) a	1.03 (0.04) c	67.9 (13.5) a
C30	46,044 (415) b	18.8 (0.7) a	0.96 (0.03) c	40.9 (4.7) b
C50	49,370 (545) a	21.2 (1.0) a	0.88 (0.03) d	64.1 (8.4) a

3.4. Bulk Density and Infiltration Rate

Eleven months after plot establishment, the control treatment resulted in lower water content ($p < 0.01$) and increased bulk density ($p < 0.0001$) compared to the compost incorporated treatments (Table 3). There were no differences in water content between compost treatments. The C50 treatment resulted in the lowest bulk density at 0.88 g cm^{-3}, followed by the C30 (0.96 g cm^{-3}), U30 (1.03 g cm^{-3}), C10 (1.19 g cm^{-3}), and the control (1.35 g cm^{-3}). With each increase in compost application rate, there was a decrease in the bulk density ($p < 0.05$).

Compost incorporation significantly improved the IR to 36.0 to 67.9 cm h^{-1} compared to the tilled only control at 27.3 cm h^{-1} (Table 3). Mean rainfall and storm intensity from the 20 storm events were 5.66 cm and 5.47 cm h^{-1}, respectively, and these values are smaller than the measured IR. This demonstrates that, while there are differences in IR between treatments, the rainfall and storm intensity were too small to capture the differences between treatments using observed runoff from natural events.

4. Discussion

4.1. Runoff Quantity

In all cases, runoff volume was less than 10% of total rainfall across the full length of the study. The soil texture at this site is a sandy clay with 52% sand. Tilling alone was enough to loosen the soil in order to achieve high infiltration rates for this sandy soil. Two field studies at this location that also had a sandy clay soil texture included a compacted control and a tilled control [11,18]. In both studies, infiltration with compost incorporation was significantly increased compared to the compacted control but not compared to the tilled control, which is similar to the pattern observed here with no difference between tillage and tillage with compost amendment. Both prior studies had a till depth of 30 cm, which was twice the depth the soil was tilled in this experiment. The amount of runoff relative to rainfall was similarly low to tillage in the previous studies.

4.2. Runoff Water Quality

The TSS values are generally lower than other studies monitoring TSS from roadway runoff with compost amendments [19,34]. The Environmental Protection Agency (EPA) has set guidelines for construction and development point source category for turbidity at 280 NTU [35]. All reported turbidity values are less than half of the EPA requirement. The average turbidity from this experiment (21 NTU) was also below the North Carolina Department of Environmental Quality (NCDEQ) surface water quality standards for aquatic life and secondary recreation for both freshwater (<50 NTU) and saltwater (<25 NTU) [36]. Runoff turbidity was much higher in a similar study at this site, possibly due to slower vegetation establishment in a fall establishment versus a spring establishment in this experiment [37]. However, the average turbidity reported here would be unsuitable for sensitive water bodies such as trout streams (<10 NTU) [36].

Dissolved nutrients and heavy metals were lower than other studies using compost on roadsides [10,19,34,38–40] and below the reported EPA national average [17]. The delay in the PO_4^{3-} export from both soil and compost was also seen in other studies [19,34]. The pattern of Cu export was similar to the one observed by Rivers et al. [19]; they observed that Cu export temporarily increased before decreasing in the first few storm events. The Zn leaching pattern observed here mimics the pattern observed by Wissler et al. [40], where Zn levels are consistent over time. However, Rivers et al. [19] observed a flush of Zn in the first few storm events before it dramatically decreased. Additionally, there were few differences between treatments, suggesting that compost, at a rate of up to 50% by volume, might not increase nutrient and heavy metal loads in runoff. This field study demonstrated that compost did not decrease nor increase water quality in terms of turbidity, TSS, and dissolved nutrients and heavy metals.

4.3. Vegetation Establishment

A study using a mixed source compost in a sandy loam soil also found that biomass was significantly increased with both the 2.5 and 5.0 cm compost applications compared to the no compost control [12]. Their maximum reported biomass was 260 kg ha^{-1}, which is drastically lower than any of the values reported in this study. The minimum value in this study was 367 kg ha^{-1} for U30 treatment on Day 51, and the maximum value was 4205 kg ha^{-1} for C50 treatment on Day 96 (Figure 6). Environmental factors as well as compost source could influence the differences for biomass produced. Another study found that compost increased vegetative cover compared to a no compost control at three of four field locations [11]. Other studies have reported better vegetation establishment in disturbed soils with compost amendments using a visual assessment [10,19].

Overall, all treatments in this study had dense vegetative coverage, largely composed of volunteer annual ryegrass. The certified compost produced more biomass compared to the uncertified compost and the control. The certified compost also led to increased biomass with increased rates of compost. The uncertified compost had higher levels of organic matter (79.7%) and carbon (30.4%), which led to a C/N ratio of 18.5 (Table 1). Higher C/N ratios are known to immobilize nitrogen, which can inhibit vegetation growth [41]. The C/N ratio of the certified compost was 12.2, which is within the ideal range for vegetation establishment [41].

4.4. Bulk Density and Infiltration Rate

The compost application rate did have an effect on bulk density and IR. Numerous studies have observed decreases in bulk density with compost incorporation [9,11,18,20] and with increasing compost rates [8]. For the certified compost, the 50% application rate resulted in higher IR compared to the 10% and 30% application rate. The U30 and C50 treatments resulted in the same IR ($p < 0.05$). The uncertified compost resembled a mulch with large pieces of woody debris present, while the certified compost was screened for finer particle size. The differences in particle sizes within the compost between the two sources could have cause the observed differences in IR. The IR values reported here are higher compared to other studies with compost incorporation in urban settings [11,13,18,19]. This field experiment also had better vegetation establishment compared to the studies mentioned above. It is possible that the strong vegetation establishment allowed for enhanced root growth and thus for a more rapid IR, as was also indicated in a previous study at this site [11,42].

5. Conclusions

The objective of this study was to determine the benefit of incorporating compost in disturbed soils for reducing runoff, improving water quality, and increasing biomass production. Tilling the soil may have been sufficient to loosen the soil and limit runoff, due to the lack of differences between treatments. Compost incorporation did not alter the sediment concentrations in runoff or dissolved nutrients and heavy metals. All water quality parameters measured were lower than similar studies incorporating compost in roadside soils. This may be due to the lower runoff volume and dense vegetation establishment observed in all treatment plots. The dense vegetation in the treatment plots could have led to higher water withdrawals and evapotranspiration during the growing season as well as improved soil structure from root growth. The strong vegetation establishment in the first month of the experiment may have also enhanced root channels in all treatments leading to the lack of differences in runoff quantity.

Certified compost did enhance biomass production, and higher rates of certified compost lead to more biomass production. The certified compost may have increase soil fertility leading to better vegetation establishment. The uncertified compost had a higher C/N ratio compared to the certified compost, which could have caused it to immobilize nutrients during vegetation establishment. Compost C/N ratio should be measured before application to make sure it falls within the ideal C/N rage for vegetation establishment. Federal and state regulations in the United States require soil to be vegetated prior to the end of construction, and compost incorporation prior to seeding has the potential to reduce the effects of compaction by decreasing the bulk density and increasing IR and vegetation establishment. The rate of vegetation establishment shortly after seeding may be an important factor in determining the effectiveness of compost incorporation. Sufficient vegetation establishment after soil disturbances may reduce the need for higher rates of compost or any compost at all, but compost clearly enhanced vegetation establishment and growth in this study. More experimentation is needed in different soils to develop standards for the use of tilling and tilling plus compost amendment on roadsides.

Author Contributions: Conceptualization, C.N.K., R.A.M. and J.L.H.; methodology, C.N.K., R.A.M. and J.L.H.; formal analysis, C.N.K.; investigation, C.N.K.; resources, R.A.M. and J.L.H.; data curation, C.N.K.; writing—original draft preparation, C.N.K.; writing—review and editing, R.A.M. and J.L.H.; supervision, R.A.M. and J.L.H.; project administration, R.A.M. and J.L.H.; funding acquisition, R.A.M. and J.L.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the North Carolina Department of Transportation, grant number RP 2019-06.

Data Availability Statement: The runoff data are available upon request from the corresponding author for all reasonable requests.

Acknowledgments: The authors appreciate the support of Adam Howard, Jamie Luther, Christopher Niewoehner, and Erin Rivers.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Batey, T.; McKenzie, D.C. Soil compaction: Identification directly in the field. *Soil Use Manag.* **2006**, *22*, 123–131. [CrossRef]
2. Olson, N.C.; Gulliver, J.S.; Nieber, J.L.; Kayhanian, M. Remediation to improve infiltration into compact soils. *J. Environ. Manag.* **2013**, *117*, 85–95. [CrossRef] [PubMed]
3. Crogger, C.G. Potential compost benefits for restoration of soils disturbed by urban development. *Compost Sci. Util.* **2005**, *13*, 243–251. [CrossRef]
4. Kranz, C.N.; McLaughlin, R.A.; Johnson, A.; Miller, G.; Heitman, J.L. The effects of compost incorporation on soil physical properties in urban soils—A concise review. *J. Environ. Manag.* **2020**, *261*, 110209. [CrossRef] [PubMed]
5. Craul, P.J. *Urban Soils: An Overview and Their Future in Landscape Below Ground*; Wason, G.W., Neely, D., Eds.; International Society of Arboriculture: Savoy, IL, USA, 1994.
6. Schafer-Landefeld, L.; Brandhuber, R.; Fenner, S.; Koch, H.-J.; Stockfisch, N. Effects of agricultural machinery with high axle load on soil properties of normally managed fields. *Soil Tillage Res.* **2004**, *75*, 75–86. [CrossRef]
7. Shestak, C.J.; Busse, M.D. Compaction alters physical but not biological indices of soil health. *Soil Sci. Soc. Am. J.* **2005**, *69*, 236–246. [CrossRef]
8. Agassi, M.; Hadas, A.; Benyamini, Y.; Levy, G.J.; Kautsky, L.; Avrahamov, L.; Zhevelev, H. Mulching effects of composted MSW on water percolation and compost degradation rate. *Compost Sci. Util.* **1998**, *6*, 34–41. [CrossRef]
9. Crogger, C.; Hummel, R.; Hart, J.; Bary, A. Soil and redosier dogwood response to incorporated and surface-applied compost. *Hortscience* **2008**, *43*, 2143–2150. [CrossRef]
10. Logsdon, S.D.; Sauer, P.A.; Shipitalo, M.J. Compost improves urban soil and water quality. *J. Water Resour. Prot.* **2017**, *9*, 345–357. [CrossRef]
11. Mohammadshirazi, F.; McLaughlin, R.A.; Heitman, J.L.; Brown, V.K. A multi-year study of tillage and amendment effects on compacted soils. *J. Environ. Manag.* **2017**, *203*, 533–541. [CrossRef]
12. Evanylo, G.K.; Porta, S.N.; Li, J.; Shan, D.; Goatley, J.M.; Maguire, R. Compost practices for improving soil properties and turfgrass establishment and quality on a disturbed urban soil. *Compost Sci. Util.* **2016**, *24*, 136–145. [CrossRef]
13. Alshraah, S.H. Soil Tillage for Stormwater Infiltration: Effects of Amendments and Vegetation Type over Time. Ph.D. Thesis, North Carolina State University, Raleigh, NC, USA, 2020.
14. Violin, C.R.; Cada, P.; Sudduth, E.B.; Hassett, B.A.; Penrose, D.L.; Bernhardt, E.S. Effects of urbanization and urban stream restoration on the physical and biological structure of stream ecosystems. *Ecol. Appl.* **2011**, *21*, 1932–1949. [CrossRef] [PubMed]
15. Bartens, J.; Day, S.D.; Harris, J.R.; Dove, J.E.; Wynn, T.M. Can urban tree roots improve infiltration through compacted subsoils for stormwater management? *J. Environ. Qual.* **2008**, *37*, 2048–2057. [CrossRef] [PubMed]
16. Hinman, C. *Bioretention Soil Mix Review and Recommendations for Western Washington*; Washington State University: Pullman, WA, USA, 2009. Available online: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.431.4124&rep=rep1&type=pdf (accessed on 7 November 2021).
17. Pitt, R.; Lantrip, J.; Harrison, R.; Henry, C.L.; Xue, D. *Infiltration through Disturbed Urban Soils and Compost-Amended Soil Effects on Runoff Quality and Quantity*; USEPA Report 600/R-00/016, NTIS PB2000-102012; Government Printing Office: Washington, DC, USA, 1999.
18. Mohammadshirazi, F.; Brown, V.K.; Heitman, J.L.; McLaughlin, R.A. Effects of tillage and compost amendment on infiltration in compacted soils. *J. Soil Water Conserv.* **2016**, *71*, 443–449. [CrossRef]
19. Rivers, E.N.; Heitman, J.L.; Mclaughlin, R.A.; Howard, A.M. Reducing roadside runoff: Tillage and compost improve stormwater mitigation in urban soils. *J. Environ. Manag.* **2021**, *280*, 111731. [CrossRef]
20. Curtis, M.J.; Claassen, V.P. Regenerating topsoil functionality in four drastically disturbed soil types by compost incorporation. *Restor. Ecol.* **2009**, *17*, 24–32. [CrossRef]
21. Chahal, M.K.; Shi, Z.; Flury, M. Nutrient leaching and copper speciation in compost-amended bioretention systems. *Sci. Total Environ.* **2016**, *556*, 302–309. [CrossRef]
22. Mullane, J.M.; Flury, M.; Iqbal, H.; Freeze, P.M.; Hinman, C. Intermittent rainstorm causes pulses of nitrogen, phosphorus, and copper in leachate from compost in bioretention systems. *Sci. Total Environ.* **2015**, *537*, 294–303. [CrossRef]
23. Tirpak, R.; Nabiul Afrooz, A.R.M.; Winston, R.J.; Valenca, R.; Schiff, K.; Mohanty, S.K. Conventional and amended bioretention soil media for targeted pollutant treatment: A critical review to guide the state of practice. *Water Res.* **2021**, *189*, 116648. [CrossRef]
24. USDA; NRCS. Web Soil Survey. 2016. Available online: https://websoilsurvey.sc.egov.usda.gov/ (accessed on 3 June 2020).
25. NCDOT. Erosion and Sediment Control Guidelines. 2015. Available online: https://connect.ncdot.gov/resources/hydro/HSPDocuments/NCDOT_ESC_Manual_2015_.pdf (accessed on 12 April 2021).
26. Gee, G.W.; Bauder, J.W. Particle-size analysis. In *Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods*, 2nd ed.; Klute, A., Ed.; SSSA: Madison, WI, USA, 1986.
27. Clesceri, L.S.; Greenberg, A.E.; Eaton, A.D. *Standard Methods for the Examination of Water and Wastewater*, 20th ed.; American Public Health Association, American Water Works Association, Water Environmental Federation: Washington, DC, USA, 1998; pp. 3-37–3-43.
28. O'Dell, J.W. *Method 180.1: Determination of Turbidity by Nephelometry*; United Stated Environmental Protection Agency: Washington, DC, USA, 1993. Available online: https://www.epa.gov/sites/production/files/2015-08/documents/method_180-1_1993.pdf (accessed on 10 April 2021).

29. Rice, E.W.; Baird, R.B.; Eaton, A.D.; Clesceri, L.S. *Standard Methods for the Examination of Water and Wastewater*; American Public Health Association: Washington, DC, USA, 2012; p. 541.
30. Reynolds, W.D.; Elrick, D.E.; Youngs, E.G. Single-ring and double-ring or concentric-ring infiltrometers. In *Methods of Soil Analysis: Part 4 Physical Methods*; Dane, J.H., Topp, G.C., Eds.; SSSA: Madison, WI, USA, 2002.
31. Reynolds, W.D.; Elrick, D.E. Ponded infiltration from a single ring: I. analysis of steady flow. *Soil Sci. Soc. Am. J.* **1990**, *54*, 1233–1241. [CrossRef]
32. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2021.
33. Zuur, A.; Ieno, E.N.; Walker, N.; Saveliev, A.A.; Smith, G.M. *Mixed Effects Models and Extensions in Ecology with R*; Springer Science & Business Media: New York, NY, USA, 2009.
34. Faucette, L.B.; Jordan, C.F.; Risse, L.M.; Cabrera, M.; Colman, D.C.; West, L.T. Evaluation of stormwater from compost and conventional erosion control practices in construction activities. *J. Soil Water Conserv.* **2005**, *60*, 288–297.
35. U.S. EPA. *Water: Monitoring and Assessment: 5.5 Turbidity*; U.S. EPA: Washington, DC, USA, 2012.
36. *Surface Water Quality Standards, Criteria, and In-Stream Target Values*; North Carolina Division of Water Resources: Raleigh, NC, USA, 2019. Available online: https://deq.nc.gov/documents/nc-stdstable-06102019 (accessed on 29 May 2021).
37. McLaughlin, R.A.; Brown, T.T. Performance of erosion control materials and polyacrylamide under field and rainfall simulator conditions. *J. Am. Water Res. Assoc.* **2006**, *42*, 675–684. [CrossRef]
38. Kayhanian, M.; Suverkropp, C.; Ruby, A.; Tsay, K. Characterization and prediction of highway runoff constituent event mean concentration. *J. Environ. Manag.* **2007**, *85*, 279–295. [CrossRef] [PubMed]
39. Winston, R.J.; Lauffer, M.S.; Narayanaswamy, K.; McDaniel, A.H.; Lipscomb, B.S.; Nice, A.J.; Hunt, W.F. Comparing bridge deck runoff and stormwater control measure quality in North Carolina. *J. Environ. Eng.* **2015**, *141*, 04014045. [CrossRef]
40. Wissler, A.D.; Hunt, W.F.; McLaughlin, R.A. Hydrologic and water quality performance of two aging and unmaintained dry detention basins receiving highway stormwater runoff. *J. Environ. Manag.* **2020**, *255*, 109853. [CrossRef]
41. Wortman, C.S.; Shapiro, C.A.; Tarkalson, D.D. *Composting Manure and Other Organic Materials*; University of Nebraska Lincoln Extension: Lincoln, NE, USA, 2006. Available online: https://extensionpublications.unl.edu/assets/pdf/g1315.pdf (accessed on 4 January 2022).
42. Haynes, M.A.; McLaughlin, R.A.; Heitman, J.L. Comparison of methods to remediate compacted soils for infiltration and vegetative establishment. *Open J. Soil Sci.* **2013**, *3*, 225–234. [CrossRef]