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Authors	Hurley, Stephanie;Shrestha, Paliza;Cording, Amanda
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Nutrient Leaching from Compost: Implications for Bioretention and Other Green Stormwater Infrastructure

Stephanie Hurley¹; Paliza Shrestha²; and Amanda Cording³

Abstract: Compost is often used as a soil amendment in gardens, agricultural fields, and other landscaped systems to alter soil biophysical characteristics and increase availability of valuable nutrients including nitrogen (N), phosphorus (P), and carbon (C). However, leaching of soluble nutrients from compost is of concern, particularly in wet settings, such as within green stormwater infrastructure, riparian areas, and floodplains. This research highlights the importance of saturation as an influencing factor on the nutrient leaching potential of different composts and compost-amended bioretention soils. Nutrient leaching potential was evaluated for five different compost types and two compost-amended bioretention soil mixes under increasing saturation durations, measured at 10 min, 1 day, 5 days, and 10 days of saturation. Results indicated significant increases in NH_4^+ concentrations in leachate for all composts and bioretention media from 10 min to 10 days. Over the same time period results showed decreases in NO_3^- concentrations in the leachate from all five composts, but an increase in NO_3^- concentration for one compost-amended bioretention media and no significant change in the other bioretention media. In response to increased saturation durations, PO_4^{3-} concentrations in the leachate were found to significantly increase at each stage, from 10 min, to 1 day, to 5 days, to 10 days; overall there were higher PO_4^{3-} concentrations in the leachate from the five composts than in the leachate from the two bioretention mixes. DOI: 10.1061/JSWBAY.0000821. This work is made available under the terms of the Creative Commons Attribution 4.0 International license, <http://creativecommons.org/licenses/by/4.0/>.

Introduction

Compost is the product of biological decomposition of organic substrates either under thermophilic conditions (temperatures that exceed 50°C), which kill pathogens and plant seeds (Haug 1993), or through the use of organisms such as earthworms (vermicompost), which convert raw or partly decomposed organic material into compost (Abbasi et al. 2009). Compost is often used as a soil amendment in gardens, agricultural fields, and other landscaped systems; its incorporation into soil increases the supply of valuable nutrients including nitrogen (N), phosphorus (P), and carbon (C) (Fortuna et al. 2003; Castaldi et al. 2005). Some of the nutrients in compost are organically bound and insoluble, making them unavailable for immediate utilization by vegetation. Compost undergoes a microbially-mediated mineralization process in which nutrients like ammonium (NH_4^+), nitrate (NO_3^-), and phosphate (PO_4^{3-}) are released in inorganic, soluble forms that can be utilized by plants (Schlesinger 1997; Brady and Weil 2008). This slow release of organically bound nutrients is controlled by mineralization rates (Gutser et al. 2005) and makes compost less susceptible to large nutrient losses during a single rain event, unlike inorganic fertilizers that are readily soluble and

therefore transportable with water. Such qualities make compost a valuable resource in an agricultural setting. However, the soluble nutrient component of compost is important to consider in terms of leachability when used outside of the traditional agricultural or horticultural applications, such as in areas prone to saturation (e.g., shores, riparian zones, floodplains), and specifically in stormwater management systems. Nutrients present in composts are susceptible to solubilization and transport during rain events. Nutrients leaching from compost-amended soils are a cause for concern as they could potentially exacerbate existing eutrophication problems, which threaten the health of coastal and freshwater systems (Carpenter et al. 1998; Howarth and Marino 2006). The effects of extended periods of saturation on nutrient loss from compost are not well known.

The integration of green stormwater infrastructure (GSI) into the landscape has the potential to address both water quality and quantity issues (Davis et al. 2009). Two popular types of GSI are bioretention systems and constructed gravel wetlands (UNHSC 2009). Bioretention systems use native vegetation and engineered soils (soils composed of mineral particles imported to a site to enhance hydrologic processes) to capture and filter stormwater runoff, contributing to the uptake of pollutants and reduction of runoff volume. As runoff percolates through the bioretention media, sediments and pollutants undergo physical (e.g., filtration), biological (e.g., plant uptake, microbial denitrification), and physiochemical (e.g., removal of dissolved phosphorus through sorption) processes (Davis et al. 2009; Passeport et al. 2009). Gravel wetlands, which can be suitable retrofits to existing stormwater ponds, typically consist of a series of horizontal flow-through treatment cells that remain constantly saturated like a natural wetland (UNHSC 2009). Stormwater passes through a gravel substrate where algae and microbes proliferate and favor nitrate removal via denitrification (UNHSC 2009).

Compost and other types of organic matter are often recommended as a component of engineered soil media for GSI, including bioretention, constructed gravel wetlands (e.g., NJDEP 2014),

¹Assistant Professor, Dept. of Plant and Soil Science, Univ. of Vermont, 221 Jeffords Hall, 63 Carrigan Dr., Burlington, VT 05405 (corresponding author). E-mail: stephanie.hurley@uvm.edu

²Ph.D. Candidate, Dept. of Plant and Soil Science, Univ. of Vermont, 230 Jeffords Hall, 63 Carrigan Dr., Burlington, VT 05405.

³Affiliate Faculty, Univ. of Hawaii, Water Resources Research Center, 238 Holmes Hall, 2540 Dole St., Honolulu, HI 96822.

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and floating treatment wetlands (Tanner and Headly 2011). Compost amendments aid in plant growth by providing nutrients and substrate and modifying soil structure to improve infiltration; compost has exhibited good water filtering performance for removal of some metals [copper, by contrast, was recently shown to leach by Mullane et al. (2015)]; however, nutrient leaching from treatment systems has also been attributed to compost and other organic matter (Hsieh and Davis 2005; Bratieres et al. 2008; Thompson et al. 2008; Davis et al. 2009; Lefevre et al. 2015; Mullane et al. 2015).

Importantly, all composts are not created equal. Many practitioners and contractors may not be aware that there is a wide variety of composts available and that innate nutrient content, nutrient leaching potential, bacterial community composition, and other qualities vary by the feedstocks used to create the compost, the age of the compost, and the process through which the compost was produced (e.g., in windrows, static pile, vermicompost) (Confesor et al. 2009; Prasad 2010; Chatterjee et al. 2013; Neher et al. 2013). Specifications (if provided) for the type of compost to be used, and its nutrient content, are not consistent across GSI projects.

In 2014, the University of Vermont Bioretention Laboratory conducted a study of nutrient leaching potential from five different compost types under increasing saturation durations. The study also evaluated two bioretention soil mixes, which contain a proportion of compost by design. The soluble nutrients from compost, and bioretention soil media amended with compost, were investigated specifically with regards to saturation duration in this study. The research goal was to determine whether leaching of soluble nutrients (P and N), as measured by phosphate (PO_4^{3-}), nitrate (NO_3^-), and ammonium (NH_4^+) concentrations, changes with increasing saturation duration.

Methods

Composts used in the study included thermophilic compost and vermicompost. The authors also tested two locally available engineered bioretention soil mixes, which contained approximately 40 and 4% compost, respectively. Nutrient concentrations under a range of saturation conditions were compared to examine whether leachate concentrations changed over time. The four saturation times evaluated were 10 min, 1 day, 5 days, and 10 days. These saturation durations allowed for the investigation of changes in nutrient concentrations over time due to leaching from the composts and compost-amended bioretention media. The 10-min saturation was designed to mimic precipitation that runs through the compost immediately following a short duration rain event. The 1-day (24 h)

saturation was designed to mimic a longer rain event, which might cause localized ponding due to saturated subsoil. The 5-day and 10-day (120 and 240 h) saturation events were designed to mimic the leachate potential of compost during flood events. Soluble nutrient components (PO_4^{3-} , NO_3^- , and NH_4^+) of the leachate from five compost types and two bioretention mixes were evaluated to study their response to increasing saturation duration. The effects of treatments are compared across time (from one saturation duration to the next) and among experimental units (compost and bioretention media types).

Mature compost samples were donated by different local suppliers in Vermont in the spring of 2014, and information about the origins of composts was collected from the producers (Table 1). They were manufactured from various combinations of feedstocks (Table 1). One compost-amended bioretention soil media contained 60% sand and 40% compost in the mix, where compost was derived from cow manure, food scraps, and wood shavings (Table 1). The second bioretention soil mix included approximately 4% compost, specified as a low-P compost mix, decomposed from leaves and yard waste, and containing no animal waste, per the specifications of Grade 2 compost described by Minnesota Department of Transportation (MNDOT 2005) (Table 1). Compost samples from Vermont vendors were collected from three different locations within each compost pile (bottom, middle, top), and were refrigerated in polyethylene bags until August to preserve the samples and slow microbial activity. At the start of the experiment, compost samples were left to air dry in the laboratory for three days to gradually bring them up to room temperature so as to avoid a possible sudden burst of microbial activity (Bartlett and James 1980). A subsample was taken from each bag and oven dried at 50°C for one hour to enable sieving. As relatively homogeneous samples were required to adequately compare nutrient release conditions among samples, dried samples were sifted with a 2 mm sieve to remove large particles (e.g., stones, coarse woody debris). Basic nutrients and heavy metals tests were conducted on the samples (Table 2) as per the USEPA SW846-3051A (USEPA 2007) Method.

Nutrient Leachate Experiment (NH_4^+ , NO_3^- , PO_4^{3-})

A modified version of the U.S. Geological Survey field leach test was used to set up the laboratory nutrient leachate experiment (Hageman 2007). A total of 40 g of sieved sample were added to a 1-L wide mouth Nalgene bottle containing 800 mL of deionized water (20 parts water to 1 part solid ratio). Bottles were arranged in a complete block design with seven treatments and five replicates

Table 1. Compost Types and Associated Feedstock

Compost type	Feedstocks of compost	Approximately age at the time of collection
A	Leaves, wood chips, food residuals (preconsumer and postconsumer)	14–15 months
B	Cow manure, horse manure, food scraps, beer residuals (hops, yeast), wood chips, wood shavings, coffee grounds, coffee chaff	1 year
C	Food scraps, cow manure, heifer bedding, horse manure, hardwood chips, possibly straw	At least 8 months old
D	Vermicompost. Same recipe as Sample C but fed to worms starting 4–6 weeks	At least 8 months old
E	Hay, chicken manure, cow manure, horse manure, food scraps, kitchen scraps	9–10 months
	Compost-amended bioretention soil	
F	Cow manure, food scraps, wood shavings	1 year
G	Leaves and/or yard waste	^a

Note: Researchers obtained feedstock and age information from compost producers.

^aProducer informed researchers that compost in mix was Grade 2 compost, made based on specification derived from Minnesota Department of Transportation (MNDOT 2005).

Table 2. Physiochemical Properties of the Composts (Samples A–E) and Compost-Amended Bioretention Soil Mix (Samples F–G)

Parameters	Composts and compost-amended bioretention media						
	A	B	C	D	E	F	G
Total solids (dry matter, %)	55.70	58.40	55.00	62.30	49.40	99.60	99.00
pH	8.09	6.50	9.22	7.67	8.96	8.28	7.80
Electrical conductivity (dS/m)	2.57	2.08	1.85	3.32	1.43	0.73	0.21
Bulk density (g/cm ³)	0.28	0.24	0.27	0.34	0.27	1.37	0.97
Organic matter (%)	37.52	48.38	34.64	30.12	31.47	1.50	4.00
Carbon (total, %)	20.99	26.97	23.96	20.78	21.33	0.98	1.93
Nitrogen (total, %)	1.54	1.95	1.48	1.44	1.32	0.22	0.12
C:N ratio	13.61	13.82	16.24	14.42	16.14	4.42	16.08
NH ₄ -N (mg/kg)	1.78	6.67	1.61	2.00	2.42	2.86	1.80
NO ₃ -N (mg/kg)	505	548	1.10	758	2.94	95	3.00
Phosphorus (total, %)	0.31	0.32	0.27	0.27	0.28	0.06	0.10
Potassium (total, %)	0.86	1.33	0.92	0.78	0.82	0.07	0.18
Total calcium (%)	2.46	1.29	1.46	1.29	2.35	0.32	0.42
Total magnesium (%)	0.57	0.58	0.62	0.59	0.51	0.31	0.46
Total sodium (%)	0.17	0.17	0.15	0.14	0.15	0.01	0.02
Total sulfur (%)	0.20	0.25	0.17	0.17	0.25	0.01	0.02
Total heavy metals (mg/kg)							
Cu	41	30	29	26	35	11	24
Fe	9,190	12,604	8,742	9,073	10,926	14,932	18,243
Al	6,296	8,394	5,306	5,571	6,735	5,292	10,303
Mn	541	523	419	335	506	298	455
Zn	115	84	81	200	85	25	60
Cd	<2	<2	<2	<2	<2	<2	<2
Cr	20	15	25	27	19	44	24
Ni	13	13	19	19	16	23	22
Pb	25	8	5	5	7	5	6

per treatment. Before extracting water, the contents in the bottle were shaken for 5 min and allowed to settle for 10 min. Water samples were drawn with a 20-ml polypropylene syringe immediately after 10 min, and at times 24 h, 120 h (5 days), and 240 h (10 days) following the initial sampling. Two replicates of leachate from each bottle were taken at each of the four saturation times. Water samples were filtered using a 0.45- μ m nylon membrane filter and the filtrate was analyzed for ammonium (NH₄⁺), nitrate (NO₃⁻), and phosphate (PO₄³⁻) concentrations by Lachat colorimetric flow injection system (APHA 1998).

Statistical Analysis

The mean of replicates was used as the experimental unit. The effects of the saturation duration on the leaching of NH₄⁺, NO₃⁻, and PO₄³⁻ from the different media types was analyzed using repeated measures (proc mixed model) ANOVA analysis in SAS software. Fisher's least significant difference (LSD, $\alpha = 0.05$) was used to test for significant differences among saturation durations for each compost and bioretention mix. The Shapiro-Wilk normality test was conducted on the data, and appropriate transformations were carried out if the equal variance assumptions required by ANOVA were not met.

Results

The results indicate that saturation duration significantly affected concentrations of NH₄⁺, NO₃⁻, and PO₄³⁻ in the leachate water ($p < 0.0001$, Table 3). Additionally, significant differences in the overall leachate concentrations among compost types [$p < 0.0001$; Figs. (1–3)], and interaction between composts and saturation times ($p < 0.0001$), were observed (Table 3). Nutrients increased or decreased depending on the nutrient parameter and media type over saturation durations. Significant differences were observed in the nutrient leaching capacity of the various materials at each saturation time (p values ranging from <0.0001 to <0.02 ; Fig. 4).

Comparison by Nutrient across Composts and Compost-Amended Bioretention Soil Mixes

Ammonium

The NH₄⁺ concentrations in the compost leachate were approximately three times lower than NO₃⁻ concentrations in the study. Additionally, fewer significant treatment differences were seen for NH₄⁺ compared to NO₃⁻ and PO₄³⁻. Overall, leachate from compost Samples A and B had the highest NH₄⁺ concentrations relative to other composts and compost-amended bioretention soils,

Table 3. Treatment and Saturation Time Effects on the Leaching of NH₄⁺, NO₃⁻, and PO₄³⁻ Concentrations from Repeated Measures ANOVA

Factors	NH ₄		NO ₃		PO ₄	
	F(n,d)	Significant	F(n,d)	Significant	F(n,d)	Significant
Treatment	454.38 (6, 27)	<0.0001	1,376.33 (6, 27)	<0.0001	148.50 (6, 27)	<0.0001
Time	978.59 (3, 25)	<0.0001	536.96 (3, 25)	<0.0001	638.16 (3, 25)	<0.0001
Treatment \times time	121.91 (18, 41.5)	<0.0001	92.66 (18, 41.5)	<0.0001	26.09 (18, 41.5)	<0.0001

Note: Treatment refers to the different compost and compost-amended bioretention soil samples from which leaching occurred, and time refers to the saturation periods of 10 min, and 24, 120, and 240 h.

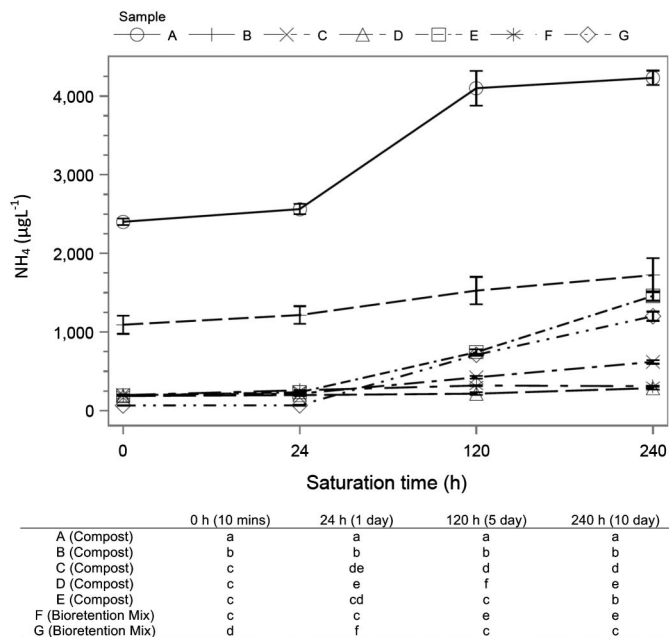


Fig. 1. Mean NH_4^+ \pm SEM concentrations measured at different saturation durations for various composts and compost-amended bioretention soils; the matrix represents mean separation using Fisher's LSD where lowercase letters in each column indicate significant differences among composts for each saturation time at $p < 0.05$; see Appendix S1 for mean values

respectively. The NH_4^+ concentrations in Sample A were significantly higher ($p < 0.01$) at all time intervals, whereas Sample B had the next significantly highest NH_4^+ concentrations in the first three time intervals only ($p < 0.03$) (Fig. 1). Sample D

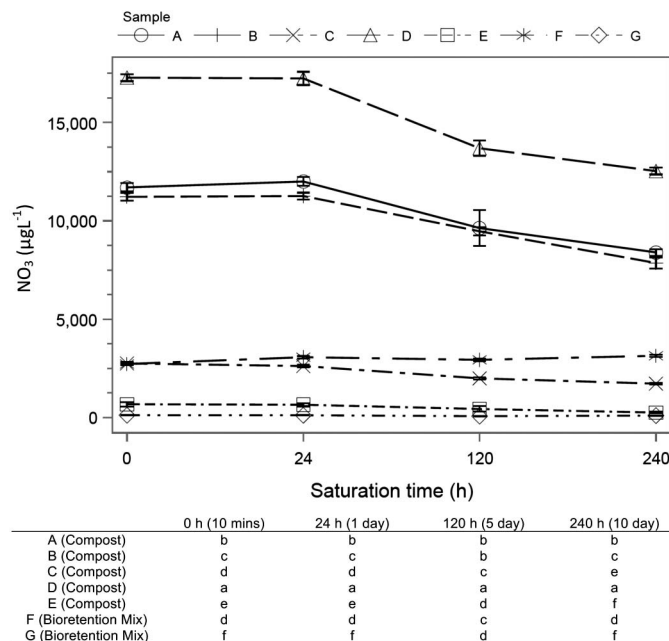


Fig. 2. Mean NO_3^- \pm SEM concentrations measured at different saturation durations for various composts and compost-amended bioretention soils; the matrix represents mean separation using Fisher's LSD where lowercase letters in each column indicate significant differences among composts for each saturation time at $p < 0.05$; see Appendix S1 for mean values

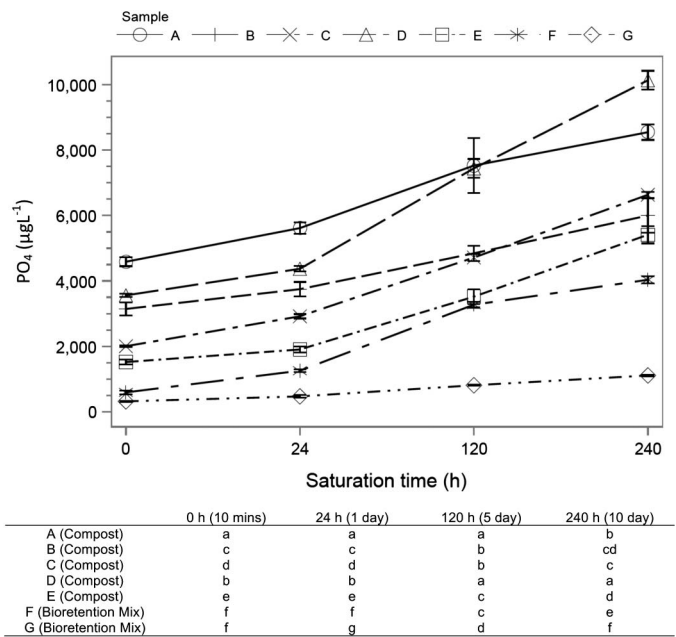


Fig. 3. Mean PO_4^{3-} \pm SEM concentrations measured at different saturation durations for various composts and compost-amended bioretention soils; the matrix represents mean separation using Fisher's LSD where lowercase letters in each column indicate significant differences among composts for each saturation time at $p < 0.05$; see Appendix S1 for mean values

(vermicompost) leachate had the lowest NH_4^+ concentrations of all the treatments after five days of saturation (Fig. 1).

Nitrate

Sample D had significantly higher NO_3^- concentrations in the leachate water relative to all the other samples ($p < 0.0005$, Fig. 2), followed by compost Samples A and B for all saturation times. The NO_3^- concentrations from the bioretention Sample G were the lowest overall, whereas the bioretention mix in Sample F had higher NO_3^- leaching than compost Samples C and E (Fig. 2).

Phosphate

Overall, PO_4^{3-} concentrations were found to be the lowest in the two compost-amended bioretention soils relative to the five compost samples for all saturation durations (Fig. 3). The PO_4^{3-} concentration in the leachate was lowest for Sample G, the bioretention mix known to be amended with low-P compost. Results for Sample G were significantly lower than bioretention Sample F at three saturation times of 1, 5, and 10 days ($p < 0.0001$), although were not significantly different at the initial 10-min duration. PO_4^{3-} concentrations were highest from thermophilic compost Sample A, and vermicompost Sample D (Fig. 3).

Effects of Saturation Duration on NH_4^+ Concentrations

The NH_4^+ percent increase in the leachate for compost Samples A to E from initial (10 min) to final (10 day) saturation time were 76, 58, 215, 54, and 654% respectively, while percent increase for bioretention Samples F and G leachate for that duration were 57 and 1,744%, respectively. The NH_4^+ concentrations in the leachate consistently increased with increasing saturation duration from all compost and bioretention media [Fig. 4(a)]. The NH_4^+ concentrations, as opposed to NO_3^- , were lowest in the vermicompost compared to thermophilic composts at all saturation events. The largest increases in NH_4^+ in all cases occurred after 24 h of saturation time.

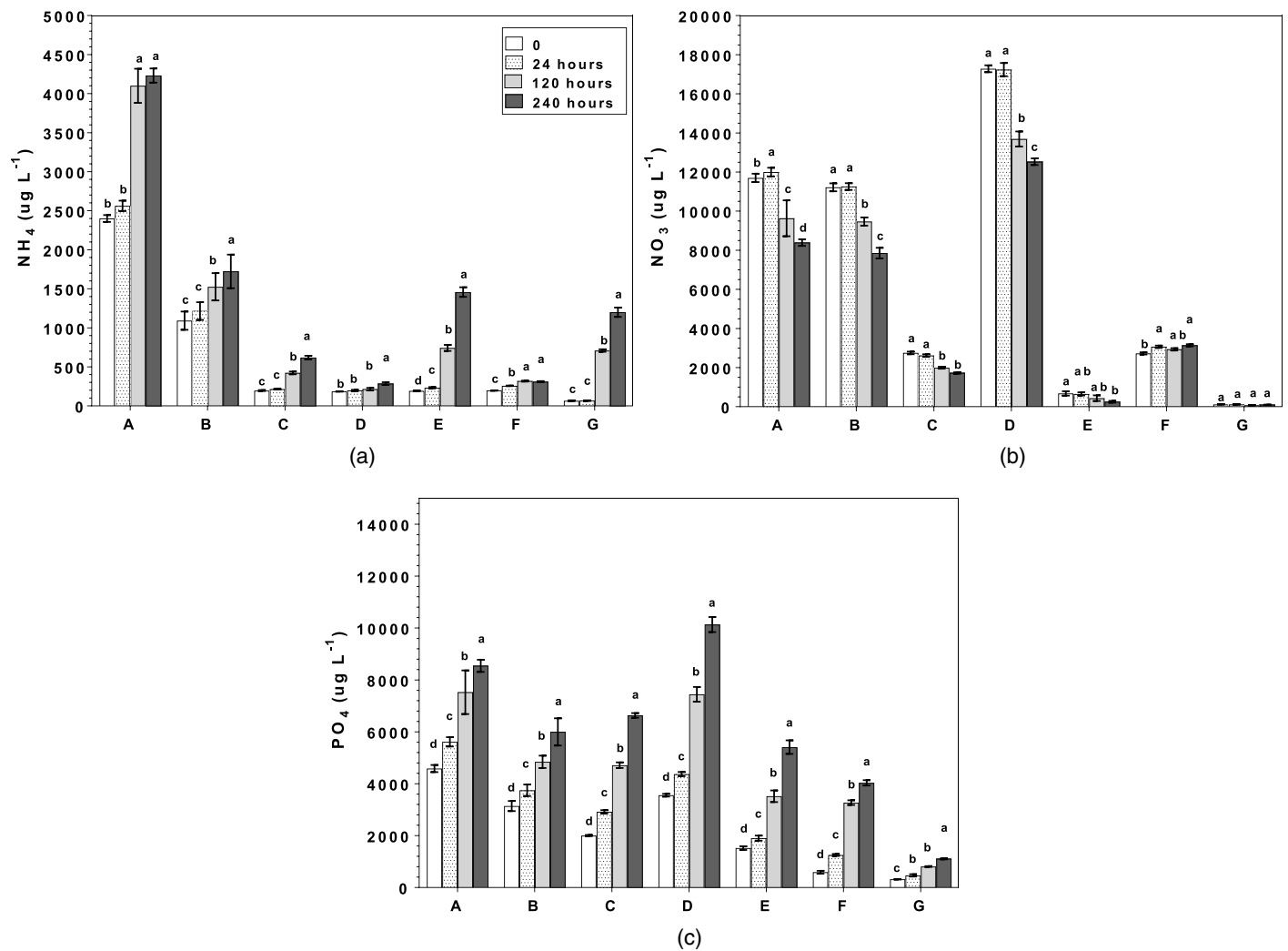


Fig. 4. (a–c) Mean \pm SEM NH_4^+ , NO_3^- , and PO_4^{3-} concentrations analyzed at each saturation duration for five compost types (Samples A–E) and two compost-amended bioretention mixes (Samples F–G); lowercase letters within each compost type and bioretention mix indicate significant differences among saturation durations

Effects of Saturation Duration on NO_3^- Concentrations

After 10 min of saturation, NO_3^- concentrations were highest in the leachate obtained from vermicompost (Sample D), followed by thermophilic composts in the order of Sample A, B, C, and E [Fig. 4(b)]. Vermicompost leachate also had the highest NO_3^- concentrations out of all compost types in all the saturation times evaluated. Between 10 min and 24 h of saturation, all compost samples and bioretention soil mixes experienced either a small increase in nitrate leachate or no change prior to beginning a fairly consistent decline after 24 h. The NO_3^- concentrations from all the compost samples, A to E, decreased by 28, 30, 37, 27, and 62%, respectively, from the 24-h saturation to the final saturation time (10 days). The reduction in NO_3^- concentrations was highly significant for all compost samples (p values ranging from <0.0001 to 0.003).

Sample F, a bioretention mix, showed an opposite trend, where NO_3^- leachate concentrations increased by 15% from initial to final saturation time, although it varied from increasing to decreasing concentrations between saturation durations, and nitrate concentrations were not significantly different between 24 h and 10 days of saturation. Sample G leachate showed reduction by 16%, similar to the compost samples, although concentrations were not shown to be significantly different among any of the saturation durations.

The concentration of NO_3^- from the bioretention mix Sample F exceeded that present in bioretention mix Sample G (as well as compost Sample E) in all cases [Fig. 4(b)].

Effects of Saturation Duration on PO_4^{3-} Concentrations

The PO_4^{3-} concentrations consistently increased with time of saturation for all composts and both bioretention media [Fig. 4(c)]. The percentage increases from initial to final saturation (all significant at $p < 0.0001$) of PO_4^{3-} in leachate from compost Samples A–E were 86, 91, 231, 185, and 256%, respectively. The percent increases for bioretention mix Samples F and G leachate for that duration were 582 and 249%, respectively, and were also significant ($p < 0.0001$, $p < 0.0012$). Sample G exhibited a significant increase in soluble PO_4^{3-} over time; however, PO_4^{3-} was present at the lowest concentrations compared to all other media for the entire study duration [Fig. 4(c)].

Discussion

This study highlights the importance of saturation as an influencing factor on the nutrient leaching potential of different composts and

compost-amended bioretention soils. This work specifically investigated the concentrations of soluble nutrients released by less than 2-mm grain size compost, and bioretention mixes amended with compost, under increasing saturation durations. Notably, none of the composts were ever applied on the land and exposed to on-site variations that would occur once applied; they were collected from producers and brought directly to the laboratory. Compost that is field-applied typically includes coarse materials such as woody debris and other larger organic materials that contribute to soil aeration, water retention, and some microbial immobilization of organic nutrients, which may affect the net rate of nutrients released (Sollins et al. 1996). Although intact compost samples (e.g., potentially containing rocks, coarse wood) were not specifically investigated in this study, sieving only removed approximately 25% of each sample; the majority of each sample passed easily through the sieve. There was natural variability among compost types, which was to be expected. Potential sources of error included variation in the compost ages and possible change in microbial populations during refrigeration and storage, as well as during the alteration of compost structure during sieving.

The results of this study indicate that PO_4^{3-} , NO_3^- , and NH_4^+ concentrations from all composts and compost-amended bioretention soils changed significantly in response to increased saturation durations [$p < 0.05$; Figs. 4(a–c)]. The PO_4^{3-} concentrations increased significantly in the leachate water over time, while the reverse occurred for NO_3^- [Figs. 4(b and c)]. Whether one should be concerned about the use of compost in design of stormwater treatment systems might depend on whether N or P is considered a target pollutant of concern. Further research is needed before the concerns should be dismissed about nitrate leaching from composts in saturated settings. Confesor et al. (2009) found that leaching of NO_3^- -N consistently increased with the maturity of compost being evaluated for composts derived from three distinct feedstocks (farm, food, and yard waste). In the current study, the largest decreases in NO_3^- in leachate occurred after 24 h of saturation [Fig. 4(b)]. The observed reduction of NO_3^- in leachate over the 10-day period can likely be attributed to microbially-mediated denitrification, which involves the reduction of NO_3^- to nitrous oxide (N_2O) and atmospheric nitrogen (N_2) gas under anaerobic conditions when carbon supplies are not limited (Basiliko et al. 2009; Bollman and Conrad 1998; Hunt et al. 2006). Compost in the water solutions may have contributed to dissolved organic carbon content facilitating denitrification. Denitrifying bacteria are naturally plentiful in soils (Conrad 1996) and as oxygen supplies are exhausted, NO_3^- readily acts as an electron acceptor for microbial respiration (Smith et al. 2003). This redox reaction occurs naturally in wetlands and bog ecosystems.

The NH_4^+ increases were likely attributable to ammonification of organically bound nitrogen (e.g., proteins, amino acids), which can occur in either aerobic or anaerobic conditions (Gumbrecht 1993). In oxygenated conditions, NH_4^+ is converted to NO_3^- in a two-step process called nitrification (Kadlec and Knight 1996; Basiliko et al. 2009). It is possible that much of the nitrate, which was likely produced during nitrification, was subsequently removed as saturation time increased via denitrification, facilitated by the anaerobic conditions in the sample bottles. In future studies measuring N_2O , which is released during denitrification, would help support this idea.

In this study P leaching significantly increased with saturation duration for all samples [$p < 0.001$; Fig. 4(c)]. This could be because of the mineralization of organic P under aerobic conditions, and increased solubility of mineral associated P under anaerobic (reduced) conditions as saturation increased. The P that is previously sorbed onto mineral [e.g., insoluble Fe(III) compounds]

and organic complexes can be desorbed and released as PO_4^{3-} under reduced conditions (Baldwin 1996; McDowell and Sharpley 2001; Bartlett and James 1993), a process that also takes place in submerged sediments in lake bottoms. PO_4 -P often limits primary productivity in water bodies (Schindler et al. 1971) and excess P can lead to toxic algal blooms, impairing water quality (Carpenter et al. 1998). Confesor et al. (2009) observed variation in leaching associated with both compost age (3–20 weeks) and feedstock (farm, food, and yard wastes), but indicated farm waste compost at the latter end of the maturity timeframe leached the greatest PO_4 -P load, even though the P concentration of the compost itself was lower than for the composts derived from other feedstocks. Other factors such as presence of human or animal pathogens in manure-derived compost are also a greater concern in wet areas than dry areas. Cutler (2016) found that *E. coli* survival declined more rapidly in composts applied to drier soils, while in wetter settings with depleted O_2 , obligate anaerobic microbes could not compete with *E. coli*, and the pathogen persisted.

The compost type and the amount incorporated into bioretention media both influenced P leaching potential [Figs. 3 and 4(c)]. Although this study only examined one type of vermicompost (Sample D), its leachate was consistently higher in PO_4^{3-} and NO_3^- than leachates from other composts, raising concern about the use of vermicompost in wet or often flooded settings. Across the two bioretention mixes, P leaching was significantly higher from pure compost samples relative to the bioretention compost-soil mixes. Results indicated significantly lower ($p < 0.0001$) PO_4^{3-} leaching from the low-P compost-based bioretention soil (Sample G) that included ~4% compost by weight, as opposed to the bioretention soil comprising 40% compost by volume (Sample F). (Differences in units of the two bioretention mixes refer to how the mix was prepared, with large batches requiring a volumetric approach.) The compost in this bioretention mix (Sample F) was also derived partly from manure, which is typically characterized by high P content (Kleinman et al. 2011). Future research should target the inclusion of additional bioretention mixes with both a broader spectrum of percent compost incorporated in the mixes, and mixes utilizing composts comprising a wider variety of feedstocks. Given the study timeline, the researchers worked with bioretention mixes that were locally available.

Notably, feedstocks incorporated by producers of compost in Vermont included many components (Table 1); no local compost producers had a compost that did not contain either food scraps or some type of manure, both of which are recommended to be excluded for low-P compost recipes (see also MNDOT 2005). For wet locations and GSI projects where P is a pollutant of concern, the authors recommend that compost have a low P content, as do Hatt et al. (2009) and Hinman (2009). After reviewing the literature and nutrient content specifications provided by numerous compost producers, the authors suggest that $\leq 0.2\%$ P be the definition of low phosphorus compost. In terms of feedstock, this means that the compost should be primarily derived from yard, leaf, and wood waste, which will decompose more slowly, as opposed to composts derived from food scraps, manure, or biosolids (the latter was not studied here) (Hinman 2009). If engineers, landscape architects, and other designers of GSI and other types of ecological restoration projects specify low-P composts for their projects, perhaps compost producers will develop a supply to meet this emerging demand.

In another recent study, Mullane et al. (2015) examined 6-month and 24-month aged compost in a laboratory column study, where the compost columns were exposed to irrigation patterns simulating a series of 33.5 mm/day storms passing through a typical bioretention cell every two weeks, allowing for compost columns to dry between storm events. The compost was composed of 80% yard

waste and 20% food waste (Mullane et al. 2015). Nutrient leaching was found to be higher for P and N in the earlier storms and lower but still significant in the latter storms, with sustained leaching of phosphorus of 3 to 4 mg/L and of nitrate/nitrite from 5 to 9 mg/L (Mullane et al. 2015). Both N and P were leached at higher rates from the 24-month aged compost treatment in the earlier simulated storms and at higher rates from the younger, six-month compost treatment in the latter storms, and while leaching overall declined with time, the onset of each new storm mobilized a new peak in nutrient pollutant concentration in the leachate (Mullane et al. 2015). Although it was a different experimental setup, the sustained leaching levels observed by Mullane et al. (2015) are comparable to the leachate concentrations observed in the current study's bioretention mix Sample F (60% sand and 40% dairy manure based compost) throughout the 10-min to 10-day study range used in this research [Figs. 4(b and c)]. Taken together, these two studies highlight the need for further research, perhaps considering both the issue examined in this study of nutrient leaching over different saturation durations, along with the capacity for composts of different types to exhibit different nutrient leaching patterns after exposure to repeated storm events. There may be an effect of initial compost nutrients flushing from green infrastructure that decreases over time and between storms, but this may be in some ways countermanded by the risk of longer-term saturation and flooding on some sites, which are likely to be exacerbated by the effects of climate change.

Based on the results of this research, the use of compost in GSI and on other wet sites warrants very careful consideration, and it would be safe to err on the side of minimizing compost of all types (particularly where the influent water is nutrient rich and/or the vegetation selected can establish without the added compost). However, in projects for which compost is deemed essential for vegetation establishment and survival, practitioners should consider spot applying the compost at the site of each plant, i.e., locating the compost where the roots of the plants can easily uptake the nutrients, rather than mixing compost throughout a soil media horizon that spans outside areas accessible by roots during plant establishment.

Conclusion

Compost has many potential benefits when added to soil as an amendment. However, these benefits need to be carefully weighed against the potential risks associated with nutrient release in saturated conditions, particularly near sensitive water bodies. This laboratory research indicates that under saturated conditions composts derived from a variety of feedstocks ($n = 5$), as well as compost-amended bioretention media ($n = 2$), all leached ammonium and phosphate at increasing concentrations over time, from 10 min to 10 days of saturation. Nitrate leached at decreasing rates over the same time period from all composts studied, with one bioretention media showing a slight increase in nitrate leaching over time, and the other media showing no significant change in nitrate leaching. Compost application should be limited for GSI projects. If compost use is deemed necessary in watersheds for which P pollution is a concern, low-phosphorus composts are recommended. Low-P compost can be created using feedstocks primarily derived from yard, leaf, and wood waste, and excluding manures, biosolids, and food scraps from compost feedstocks. Additional research that examines ways to limit both N and P leaching potential from composts and compost-amended soils is recommended. Regulating both N and P pollution is important to combat eutrophication in surface waters and protect water quality for human uses and aquatic ecosystem health.

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Supplemental Data

Appendix S1 is available online in the ASCE Library (<http://www.ascelibrary.org>).

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