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RESEARCH REPORT

EFFECT OF GEOTECHNICAL AND ENVIRONMENTAL PROPERTIES OF MARYLAND COMPOST AND COMPOST AMENDED TOPSOILS ON VEGETATION ESTABLISHMENT AND GROWTH

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16. Abstract: Poor structural properties and nutrient profiles of disturbed soils often require supplemental organic matter for promoting better vegetation establishment. Compost and compost-related products, when added to soils, have proven to enhance plant growth and improve infiltration of rainwater, thereby mitigating soil erosion and excess nutrient release through surface runoff. This study commenced with interviewing 13 SHA qualified soil producers, to gain insights into the type of compost products used in their furnished topsoil to meet the SHA organic matter (OM) requirement of 4 – 8%. From these interviews, it was determined that leaf or yard waste compost was the most sought-after material for raising OM content. However, due to high demand and limited supply, the soil producers find it difficult to procure this product. Aged mulch is second in hierarchy for preference given its high OM content, low cost and wide-spread availability. Although easily assessable, biosolids is not preferred because of its high salts content, potential odor, and regulatory requirements related to its storage and transportation. In addition to the interviews, 10 producer-provided furnished topsoil samples were tested to determine soil characteristics and susceptibility to nitrogen (N) and phosphorus (P) losses via subsurface leaching. Results indicate that predicting such losses will require more extensive testing than currently conducted by SHA. Two sets of 8–9-week greenhouse microcosm studies were conducted testing SHA spec furnished topsoils amended with shredded mulch (MAT), leaf compost (LAT), and biosolids (BAT), to compare and evaluate their performance for vegetation growth and nutrient release over time. A control, unamended soil (CUT), was also included in the studies. Each greenhouse study included sixteen tubs (4 treatments with 4 replicates) which were irrigated weekly with 1 inch of tap water over the entire tub to mimic the intensity of a 4 inch/hr rain event. Across the four soil types, greater coverage of turfgrass was found in the LAT and BAT treatments, compared to MAT and CUT, even though their OM contents were similar and fell within a tight SHA specification range of 4 – 8%. Soil C:N ratio and N content were found to be major drivers for controlling turf growth, more so than OM content itself. Water quality analyses showed that the leachate from BAT treatments contained high total nitrogen (TN) concentrations originating from the biosolids amendment. Total Phosphorus (TP) release from LAT treatments increased over time as phosphate loaded tap water was applied weekly, exceeding plant uptake needs and saturating soil P adsorption sites. MAT and BAT treatments effectively reduced tap water P levels by the end of the study. Among the tub study soils, MAT treatments showed increased hydraulic conductivity compared to other soil mixtures. Finally, all treatments used in the microcosm studies were tested for their geotechnical properties. Based on the findings of the study, the UMD research team provide eight recommendations based on soil testing, amendment types, and nutrient information that may help SHA improve specifications for expanding the use of compost and topsoil products of Maryland businesses.

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1. EXECUTIVE SUMMARY

When added to soils, organic amendments, such as compost, can provide soil nutrients essential for rapid vegetation establishment, improve soil structure, and thereby build resilience against surface runoff and erosion. While benefits of compost usage are plentiful, it is critical to study the effects of compost from different feedstock sources on soils to reduce risks associated with nutrient leaching. This work studied the effects of geotechnical and environmental properties of Maryland compost-amended topsoils on vegetation establishment and growth to provide information on the responsible use of such products such that vegetative establishment and growth are enhanced while nutrient losses are minimized. To this end, the University of Maryland (UMD) research team initiated the project by (1) interviewing the Maryland Department of Transportation (MDOT) – State Highway Administration (SHA) qualified topsoil producers to determine the factors that are considered when adding compost materials to their soils, (2) conducting a column study using various Maryland furnished topsoil products to assess nutrient leaching, (3) conducting integrated greenhouse tub studies utilizing furnished topsoils (unamended and amended) to assess vegetation establishment rates, nutrient losses, and soil nutrient availability while also testing for shear and hydraulic properties, and (4) providing recommendations to SHA on the use of organic amendments based on geotechnical assessment, environmental analysis, and plant growth performance.

To better understand the compost products used in Maryland highway soils and to maximize research efforts, qualified soil producers were interviewed to determine which products are used to amend furnished topsoil to meet SHA organic matter (OM) specifications of 4 - 8%. Based largely on cost and availability, the preferred products are composted leaf mulch and aged shredded wood mulch. The interviews also identified that although biosolids are widely available and cost effective, they are not used in significant quantities by topsoil producers. Reasons for avoidance include a concern that use of biosolids will result in unacceptable soluble salt concentrations in furnished topsoil, a desire to refrain from regulatory requirements related to the handling and long-term storage of biosolids, worry that facility neighbors will complain of odors, and concerns over the ease of incorporating fresh biosolids products. However, with limited access to composted yard waste, there is potential for future biosolids usage.

Two 8–9-week tub studies (TS1 and TS2) were conducted in the UMD Greenhouse Complex to identify the effects of three soil amendments (*MAT: mulch amended topsoil; LAT: leaf compost amended topsoil; BAT: biosolids amended topsoil*). Sixteen (4 treatments x 4 replicates) tubs measuring 51 x 74 cm were filled with 10.16 cm of either a control soil or an amended soil. Metrics such as vegetation cover, height, dry mass, and tissue nutrient concentrations; leachate and runoff quantity and quality as measured by the concentration of total organic carbon, pH, nitrogen (N), phosphorus (P), and soluble salts; and geotechnical parameters such as shear and hydraulic properties were used to compare the performance of the amended soils against each other, as well as the *unamended control soil (CUT)*. TS1 used soil samples from various Maryland soil producers, while a single base soil was used in TS2 (amended by the research team). All tub study soils met the SHA OM requirements of 4 – 8%. The tubs were placed on an incline of 4% (25:1 engineering slope) and a 1-inch rainfall was simulated using tap water every week during the experiment. The soil was seeded with the standard SHA turf grass seed mix after the first 2 inches of rainfall application.

LAT and BAT treatments outperformed MAT and CUT treatments with respect to vegetative establishment. Of the eight soils, those with lower C:N ratios (CUT2, LAT1, LAT2, BAT1, BAT2) enhanced the vegetation establishment rate while those with higher C:N ratios (CUT1, MAT1 and MAT2) did not. However, the root:shoot ratio in BAT treatments was low compared to other treatments in both studies. Concerning water quality, P concentrations in the LAT leachates increased with time compared to others due to a potential oversaturation of adsorption sites in the soil as the tap water (with approximately 0.278 to 0.355 mg-P/L) was applied every week. Despite their high soil P content, P leaching of BAT treatments was low compared to other treatments most probably due to P adsorption onto oxide minerals in the soils, under slightly acidic conditions. Good turfgrass cover and reduced P loss notwithstanding, BAT treatments contributed to the highest export of Total N because of the high concentration of N in the biosolids amendment. Shear tests revealed that the TS1 and TS2 soils were comparable to that of earthen materials with effective cohesion varying from 0.6 to 2 psi and friction angle varying from 32.5° to 40.4° when compacted the soils at their optimum water content. Hydraulic tests showed that the MAT soils had the highest saturated hydraulic conductivities at both maximum dry unit weights and tub-soil bulk densities.

<u>Based on the result of these studies, the following recommendations are made:</u>

1. SHA should establish standard protocols and methods for soil tests and reach out to local labs to communicate SHA protocols to ensure consistency between private labs and MDOT Office of Materials Technology (OMT).
2. SHA should have soil producers disclose the source of the organic matter amendment used in their topsoil, if any, when submitting soil samples. Additionally, soil test results should be considered in the context of the identified amendments.
3. To encourage wider usage of compost and compost-like products, SHA should consider adjusting furnished topsoil standards for pH and soluble salts, to match those of salvaged topsoils.
4. Information on the following parameters can be beneficial when added to SHA soil tests: *a)* C:N ratio; *b)* Total Nitrogen (to provide information on the nitrate supplying capacity of the soil); *c)* Plant available N (to aid in decisions related to nutrient management plans).
5. Producer provided soil samples are beneficial for determining the QPL status. However, SHA should consider testing furnished topsoil once it arrives at a construction site for OM, soluble salts, pH, TN, available N, P, S, and the C:N ratio. Doing so will allow SHA control over the type of amendment used to raise %OM should furnished topsoil fall below the minimum specification. Additionally, if the pH falls outside of current specifications, a pH amendment can be applied onsite. Furthermore, N (refer to #4) and P results could be used to make informed decisions about nutrient management plans.
6. Because of the high C:N ratio of mulch materials, mulch amendments should not be used to raise the concentration of soil OM without a supplemental source of nitrogen to help reduce nitrogen deficiencies following the addition of mulch to topsoil.
7. Biosolids can be used to provide a wide range of essential plant nutrients to soils with nutrient deficiencies, especially those with N and micronutrient deficiencies. If and when using biosolids to raise the OM content of soil, due to potential high N losses, it should be used at a low rate or mixed with another low-N amendment.
8. Since runoff from biosolids-amended topsoil was negligible, this research demonstrates that biosolids can be used as an amendment on slopes equal to or less than 25:1 without contributing to high N concentrations in surface runoff. However, at inclines greater than 25:1, biosolids leachate could combine with surface runoff. Since these studies determined that biosolids significantly increase N concentrations in leachate, the risk of high runoff N concentrations could be greater at steeper inclines. SHA usage of biosolids should be restricted to slopes < 25:1 until further studies are conducted.

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2. INTRODUCTION

2.1. Background

As part of its commitment to environmental protection and to help meet new requirements established in Maryland House Bill (HB) 878 (now law, State Highway Administration - Compost and Compost-Based Products – Specification, 2014), the Maryland Department of Transportation State Highway Administration continues to increase organizational knowledge for the use of novel and effective stormwater management (SWM) technologies in multi-modal transportation projects. SHA desires to evaluate the performance of select compost products and compost/soil mixes in establishing permanent vegetation as part of construction site erosion prevention systems. Controlled studies are needed to provide comparative evaluation of different compost products, mixed with (SHA specification) topsoil, in order to quantify the advantages and disadvantages of the compost-based products.

Because many forms and suppliers of compost exist throughout Maryland and because the SHA topsoil specifications are broad, it is unlikely that a single set of recommendations can be generated for optimizing compost and compost amended topsoils (CATs) for meeting physical, environmental, and rapid grass establishment requirements. Fundamental science and engineering research must be completed to match compost properties with topsoil properties to produce the optimum mix to meet SHA requirements. Thus, a study, described herein, was undertaken to investigate the effects of geotechnical and environmental properties of Maryland compost sources and CAT on vegetation establishment and growth, to ensure the responsible use of such products. The research discussed in this report summarizes the UMD's findings and recommendations.

2.2. Literature Review

2.2.1. Physical and Chemical Characteristics of Roadside Soil

Road shoulders include a subsurface layer of compacted soil and/or aggregate which supports the road surface and a thin topsoil layer intended to support vegetation that protects against erosion and runoff. When SHA-specified *furnished* topsoil is used, it is brought in from an offsite location where it is often stockpiled for months, even years, contributing to the following undesirable soil physical and chemical properties: destruction of aggregate structure, high bulk density, low water holding capacity, low microbial activity, low nutrient content and low OM content (Abdul-Kareem and McRae 1984; Block et al. 2020; Wick et al. 2009). The impacts of road design, construction activities, maintenance and traffic exacerbate these problems and contribute to other problems such as compaction, high nutrient deposition, high or low pH values, and high salinity (De Silva et al. 2021; Kim and Yoo 2021; Lagerwerff and Specht 1970; Rossi et al. 2015). These soil characteristics alone or in association with others destabilize roadways due to an insufficient vegetative cover, increasing stormwater runoff and erosion (Curtis and Claassen 2009; Haan et al. 2012; Hopkinson et al. 2016; Mills et al. 2021).

2.2.2. Problems Associated with Poor Roadside Soil Quality

The health of roadside vegetation is important because it plays an integral role in the safety, stability, and aesthetics of roadways. Rapid establishment of a grass cover is highly important since it is associated with reductions in soil erosion and stormwater runoff (Owen et al. 2019). Runoff increases erosion, which in turn worsens the evenness and quality of the vegetative cover (Ludwig et al. 2005). Thus, a positive feedback loop is founded when plant establishment fails. However, when plant cover is adequate, it intercepts rainwater, slows it down, and reduces stormwater runoff and erosion losses. Additionally, the physical properties of soil are improved through soil-root interactions, all of which lead to an opposing feedback loop (Kulmatiski et al. 2008). A final benefit of a healthy roadside plant community includes grass strips to improve stormwater quality through uptake, sedimentation, and filtration (Stagge et al. 2012). This attribute has the potential to reduce pollutants that were already present in soil as well as those that enter soil from roadway activities.

Periodic grading, compaction, and other disturbances associated with roadside construction activities can damage the structural functionality of urban soils (Gray and Sotir 1996). Topsoil or subsoil is often left bare, which predisposes it to erosion during rain events and discharge of heavy loads of sediment and nutrients (nitrogen and phosphorus) into downstream waterbodies (e.g., Chesapeake Bay) via stormwater runoff. Nutrient-rich waters promote algae growth resulting in eutrophication and hypoxia (US EPA 2015a). Additionally, stormwater sediment can sorb many trace metals (Cr, Cu, Pb, Zn) and organic pollutants such as PAHs, and PCBs (Cao et al. 2019; Masoner et al. 2019; US EPA 2015b; Zgheib et al. 2012). These contaminants have the potential to bioaccumulate and biomagnify, placing both aquatic and terrestrial species at high risk of exposure. Sediment loading is also the primary stressor on submerged aquatic vegetation growth and productivity in the Chesapeake Bay (USGS 2003).

Selecting soils with stable structure, increased soil porosity, decreased bulk density and increased water retention capacity for highway or road slopes, particularly those with steeper embankments, is vital for alleviating soil erosion and stormwater drainage/quality issues, and promoting vegetative growth. Although the physical and chemical characteristics of urban soils have been studied extensively, there are many other important variables (e.g., shear properties) that control stability, erosion, and vegetative growth. Only a few works (Duzgun et al. 2021; Puppala et al. 2007; Benson and Othman 1993) have focused on soil geotechnical properties. Knowledge of shear properties under field conditions can help evaluate the strength of soils which may be of interest for analyzing the stability of the slopes, including sloughing or shallow infinite failures (e.g., some observed in the DC metropolitan area). As transportation authorities take measures to remediate or stabilize degraded soils through chemical additives or low-impact treatments, such as the addition of organic material (OM), the effects on geotechnical properties should be investigated alongside other physical and chemical properties for a more holistic assessment.

2.2.3. Benefits of Organic Amendments

The ability for compost and compost-like products to improve roadside soil functionality is well established and recognized by the US Environmental Protection Agency, the American Association of State Highway and Transportation Officials, and several individual state highway administrations (AASHTO 2020; Birt et al. 2007; EPA 2007). Due to observed favorable outcomes with regard to improved vegetative cover and infiltration (Rivers et al. 2021; Strecker et al. 2015; Brown and Gorres 2011), the practice of using such products in surface applications or combined with tillage post-construction activities has gained popularity. An increase in shear strength and shrinkage resistance of expansive clays with biosolids and dairy manure compost addition have been observed, particularly when amended at optimum compost proportions (20 – 30%) (Puppala et al. 2007). Another study that tested for both shear and hydraulic properties showed a an order of magnitude of increase in saturated hydraulic conductivities (from 1.2×10^{-7} to $2–5.5\times10^{-6}$ cm/s and 1.2×10^{-7} to $1.7–3.6\times10^{-6}$

cm/s) between unamended topsoil and topsoil blended with leaf compost and biosolids, respectively (Duzgun et al. 2021). Therefore, improved environmental and engineering properties associated with increased soil OM content could help build resilience against erosion drivers such as rain and wind (US EPA 1997).

It is well established that CAT promotes vegetative growth by increasing nutrient content and availability; increasing microbial activity; increasing cation exchange capacity; decreasing soil bulk density; improving soil aggregation; and increasing water infiltration and water holding capacity (Kranz et al. 2020; Montemurro et al. 2004). Past research has shown that CAT improves vegetative coverage (Brown and Gorres 2011; Singer et al. 2006), and improves root health. Donn et al. (2014a) showed how CAT helps to reinforce soil on slopes through improved root growth and a study by Nguyen (2013) revealed that CAT increases total available water and plant available water, enhancing plant recovery after drought. Greater root length and mass were offered as possible explanations for higher photosynthesis and transpiration rates. Furthermore, incorporation of compost or compost-like products into soil has the potential to attenuate stormwater pollutants by plant uptake and nutrient transformations through microbial mediated activities (McPhillips et al. 2018).

2.2.4. Potential Problems Associated with Organic Amendments

Although promising, the benefits of incorporating compost products into highway topsoil must be weighed against potential negative effects. Excess application of organic amendments to soil can have adverse effects when it comes to nutrient leaching. For example, biosolids is one of the most abundantly produced and available organic materials, yet contains high levels of leachable macronutrients (N and P) (Silveira et al. 2019; Paramashivam et al. 2016) and also micronutrients (Cd, Cu, Pb, Zn) (Marguí et al. 2016; Torri and Corrêa 2012). Puppala et al. (2011) assessed runoff quality from topsoil amended with dairy-manure and biosolids and found that the chemical constituents (total phosphorus, total kjeldahl nitrogen) were high in the amended topsoils compared to the control. Similarly, Owen et al. (2021) noticed greater P-losses in both green-waste and biosolids amended topsoils. This loss of nutrients to surface water can impair downstream waterbodies and likely worsen eutrophication-related issues. Excess nutrients from organic amendments, in their dissolved form, have the potential to infiltrate through the soil profile and affect groundwater quality (and possibly potable water sources). Infiltration is especially concerning in the context of N and sulfur since P is typically immobilized and trapped in the soil matrix (Lehmann and Schroth 2002). Previous studies indicated that leaching characteristics of soils depend on the Compost source (Hansen et al. 2012; Owen et al. 2021).

2.3. Research Objectives and Goals

SHA aims to better understand leaching behavior of organic soils and amendments, to develop improved specifications for the use of compost in highway construction projects, and expand the use of compost and topsoil products in Maryland. An instructive investigation into the sources of organic materials used by Maryland soil producers and their site-specific availability is required to provide recommendations for highway topsoil specifications. In order to achieve the project goal, a three-pronged approach was used in the current study where different amended topsoil mixes were analyzed through the lens of vegetation establishment, water quality, and geotechnical properties. Specific research objectives include the following:

1. Determine which compost products SHA qualified topsoil producers use in furnished topsoil.
    a. Identify the organic products most commonly used to meet SHA organic matter specifications for furnished topsoil.
    b. Determine what factors impact compost product selection and usage.
2. Characterize Maryland furnished topsoil products by their physical and chemical properties.
3. Conduct a preliminary assessment of nitrogen and phosphorus loss via leachate of Maryland furnished topsoil based on the type of amendment used.
4. Conduct integrated greenhouse tub studies utilizing furnished topsoils (unamended and amended) to assess the following: vegetation establishment rates and overall plant health, soil nutrient content and availability, nutrient loss, nutrient uptake, runoff and leachate volumes, and saturated hydraulic conductivity.
5. Determine shear and hydraulic properties of the furnished soils used in the greenhouse tub studies.
6. Provide recommendations to SHA on the use of organic amendments based on geotechnical assessment, environmental analysis, and plant growth performance.

3. METHODOLOGY

3.1. Maryland topsoil and Compost Producer Interviews

The UMD research team applied for and received IRB approval in June 2020, to conduct interviews with topsoil producers and Maryland compost manufacturers. Invitations for participation in the research project were extended to businesses included on the 2020 SHA *List of Qualified Producers/Manufactures* for Furnished Topsoil and Compost Materials. Interview objectives included determining: (1) the source and nature of materials used in both furnished topsoil and compost; (2) the factors that drive product selection; (3) potential variability of compost products – seasonal or otherwise; (4) considerations, including SHA topsoil specifications, that are taken into account by producers when adding organic amendments; (5) the perceived effects of adding amendments to increase OM content, and (6) testing procedures and interpretation of results. Interview questions for topsoil producers and compost manufactures are included in Appendix A. All interviews were conducted via Zoom and were later transcribed into Microsoft Word documents. As stated in the IRB application and individually signed *Consent to Participate* agreement forms, all participant identities shall remain anonymous. A summary of interview findings is included in Chapter 4.

3.2. Characterization of Maryland Furnished Topsoil Samples

3.2.1. Analysis of producer furnished topsoil samples

All topsoil interview participants were asked to donate a furnished topsoil sample for analysis. Ten soil producers agreed and voluntarily disclosed the type of soil amendments used, if any, to meet SHA topsoil specifications. Three samples were not amended with organic matter, three samples were amended with leaf-compost, two were amended with finely shredded mulch, one was amended with mushroom compost, and one was amended with a combination of finely shredded mulch and biosolids. The samples were analyzed for pH, OM%, EC, total phosphorus (TP), total nitrogen (TN), cation exchange capacity (CEC) and soil texture.

3.2.2. Column Study Experimental Design

Each of the soil samples provided by interview participants was included in a short-term column nutrient leaching study to determine the loss of Total N (TN), Total P (TP) and ortho-P (OP) when the soils were leached with three rounds of deionized water. Columns (6 replicates/sample) were constructed using 130 mm Buchner Funnels (Fisher Scientific, Pittsburg, PA) and PVC pipe with an inside diameter of 118 mm. See Fig. 1. Before loading samples, a clean Whatman^{TM} 110 mm Glass Microfiber filter with a particle retention rate of 1.6 μm was placed at the base of each column. Substrate was added to a depth of 10.16 cm (4 in) - the average depth applied on SHA roadsides. Total substrate volume for each column was 1,111 cm^3. To allow water to be evenly distributed, a plastic drain coupling holding a metal end cap sat at the top of each column. Holes (1 mm) were driven into the end caps to allow water to drain evenly onto the topsoil contained within each column. Columns drained into 500 mL Büchner vacuum flasks. A vacuum system was constructed to aid drainage when columns failed to drain. Vinyl hoses connected each vacuum flask to a 6-valve manifold system. The manifold was connected to a vacuum pump which applied negative pressure to the vacuum flasks and the bottom of the soil column. Before the columns were filled with soil, each sample was sieved (U.S.A. Standard Sieve ASTM specification E-11, 4.74 mm) to allow for consistent soil bulk densities among columns. After soil was sieved and before the start of the first leaching event, 100 mL of each soil sample was preserved at -10° C. Soil samples were shipped to Agrolab, Inc (Harrington, DE) for characterization analysis.

The volume (550 mL) of water applied for the first round, simulated a 5.08 cm (2 in) rainfall event. In subsequent rounds, 275 mL of DI was applied to simulate further 2.54 cm (1 in) rain events, for a worst-case repeated 4 in rainfall scenario. Leachate samples (3 per column) were collected in three 20 mL plastic scintillation vials. Before the samples were frozen, 50 μL of H_2SO_4 (sulfuric acid) were added to each vial. The vials were stored at -10°C until the samples were analyzed as described in Section 3.6. The volume of leachate collected in each flask was recorded at the end of each round to normalize nutrient mass loss calculations (concentration X leachate volume).

3.3. Greenhouse Tub Studies

Two greenhouse microcosm studies (TS1 and TS2) were sequentially conducted in the UMD greenhouse complex to assess the effects of 3 organic soil amendments (leaf compost, finely shredded mulch, and biosolids) on soil chemical and physical properties; vegetation establishment and growth; and the quality of water either running off of the soil surface or leaching through it during and after simulated rain events. The timeline and treatments for each study are summarized in Table 1.

3.3.1. Materials

Topsoil and organic amendments were selected based on the interviews with Maryland soil and compost producers, which identified product preference and availability. The interviews established that Maryland soil producers preferred shredded wood mulch and composted yard waste to increase soil OM to meet the SHA specification of 4 - 8 %. Therefore, mulch and leaf compost were included in the tub study experiments. Although Maryland soil producers are not currently inclined to use biosolids for furnished topsoil, a biosolids-based amendment was included as a third treatment since it is widely available throughout Maryland, has ample supply and is an inexpensive source of organic material.

For TS1, the four treatments chosen were: one unamended control soil (CUT1), two organic amended soils: MAT1 (aged tree mulch amended topsoil) and LAT1 (leaf compost amended topsoil) sourced from SHA qualified Maryland topsoil producers, and the fourth soil (BAT1) was sourced from a Maryland topsoil producer and amended with a treated biosolids material that is sold as Bloom®, DC Water.

Table 1. *Timeline and treatment details for TS1 and TS2.*

General Information	TS1	TS2
Seeded:	June 1, 2021	September 13, 2021
Harvested:	July 21, 2021	November 8, 2021
Number of Rain Events:	8	9

Tub Study	Treatment	Amendment	Source of Soil	Mixed by:
TS1	CUT 1	None	Salvaged soil	NA
	MAT 1	Mulch, Sand & Sulfate	Salvaged soil*	Topsoil Producer
	LAT 1	Leaf Compost	Development near Perryville, MD	Topsoil Producer
	BAT 1	Biosolids	Development of a forested site east of the DMV	UMD Research Team
TS2	CUT 2	None	Salvaged soil*	NA
	MAT 2	Mulch	Salvaged soil*	UMD Research Team
	LAT 2	Leaf Compost	Salvaged soil*	UMD Research Team
	BAT 2	Biosolids	Salvaged soil*	UMD Research Team

* Salvaged by the same topsoil producer.

Although TS1 soils demonstrated the influence of different treatments on nutrient leaching and turf establishment, the base soil of each amendment varied in its soil properties. Therefore, to specifically test the effect of organic materials and account for any differences in the soil properties itself, the UMD team chose a control (or base) topsoil received from a Maryland topsoil producer for the second greenhouse study (TS2). The control soil (CUT2) was then amended with the following treatments: finely shredded and aged tree mulch or MAT2 (sourced from the same soil dealer who provided the TS2 base soil), composted leaves and grass clippings (Leafgro®, Maryland Environmental Services) or LAT2, and treated biosolids (Bloom®, DC Water) or BAT2. In an effort to formulate an optimal blend using each amendment, several combinations of topsoil and organic materials were blended on a w/w basis depending on the bulk density, moisture content and OM contents of the topsoil and the organic materials. A linear regression analysis was carried out with the data points on the *OM% vs percent addition (by volume) of each organic material to the topsoil* plot, to estimate the required percent of organic amendment needed to boost the soil OM to a target value of 6% (Appendix D). After determining the percent organic matter addition, TS2 treatments were mixed by researchers at UMD. All tub study treatments fell within the SHA OM% specification of 4 - 8 %, including the control (CUT2).

3.3.2. Tub Studies 1 and 2 Experimental Design

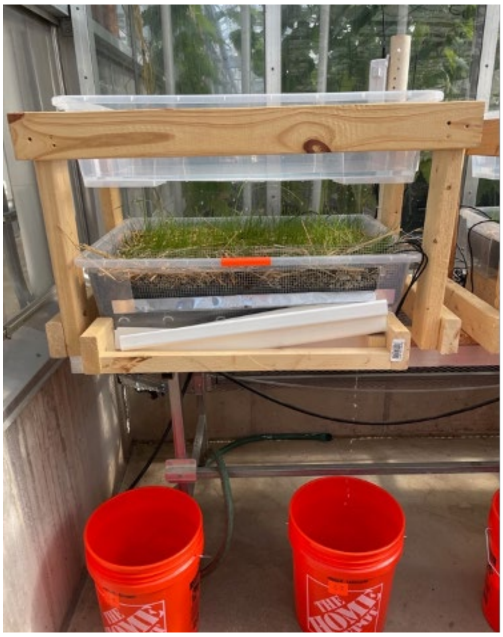


Fig. 1. *Example of a constructed Tub with a dual collection system for leachate and runoff*

Tub and Rain Simulator Construction: Each tub study consisted of sixteen (51 x 74 cm plastic tub) microcosms (4/treatment). Microcosm construction permitted leachate and runoff to be collected separately (Figure 2). Each microcosm was shimmed creating a 25:1 slope to allow water to runoff if the rainfall rate exceeded the infiltration rate.

A permeable geotextile filter (Standard duty Separation Fabric, Conservation Technology) held soil within the tubs while allowing water through holes drilled into the bottom of each tub. The geotextile satisfied the commonly used filter selection criteria (retention and anti-clogging criteria) such that the hydraulic compatibility between the geotextile filter and the overlying soil was not compromised.

Plastic gutters directed leachate and runoff to designated plastic collection buckets. The depth of soil in each tub was approximately 10.16 cm (4 in). Each tub was seeded with a standard SHA turfgrass seed mix (Newsome Seed; Fulton, MD) consisting of two tall fescue cultivars and one Kentucky Bluegrass: *Festuca arundinacea* 'Wichita' (49.39%), *Festuca arundinacea* 'Leonardo' (45.82%) and Poa pratensis 'Blue Coat' Kentucky Bluegrass (4.96%). Seeds were applied at a rate of 0.041 lbs/yd^2 (8.32 g/tub). After seeding, straw was sprinkled over treatment surfaces to mimic SHA landscaping practices and to help disperse water falling from the rain simulators.

Simulated Rain Events: In both studies, two rain events were applied before seeding the microcosms to quantify potential nutrient losses in field settings that might experience heavy storms before vegetation establishment. After seeding, weekly rain events continued for the duration of each experiment. Supplemental water was applied twice in the 7 days following seeding to aid germination. Only enough water to wet the soil surface was added and not enough to produce runoff or leachate. Otherwise, weekly rain events (8,720 mL equivalent to a 1 in rainstorm) were applied to each tub at an approximate rate of 10.16 cm/hr (4 in/hr). A removable rain simulator consisting of a plastic tub was suspended approximately 25.4 cm (10 in) above the microcosms. Holes (18 - 21) were randomly drilled into the plastic tubs in a pattern that would provide relatively equal rainfall over the surface of the microcosms. Drainage time for each rain simulator was measured to ensure consistency. Tap water was chosen as a representative for rainwater in the tub studies.

Water Sample Collection: Leachate and runoff samples were collected in clean 22.7 L (5 Gal) plastic buckets. Volume of the water samples were measured using a clean, acid-washed (5% HCl) plastic 1000 mL plastic pitcher and two plastic graduated cylinders (500 mL and 1000 mL). After the volume was measured, a 1-liter subsample was transferred into 1-liter HDPE bottles for weekly laboratory analysis. Additionally, 1 liter of tap water (control) that was applied as rainwater, was also collected for analysis. For each rain event, a second set of leachate samples was collected in 75 mL plastic bottles and shipped overnight to AgroLab, Inc.

for comparative analyses. A detailed protocol for measuring leachate and runoff volume and sample collection is found in Appendix B.

3.4. Analysis of Soil Chemical Properties

All soil samples used in this study were tested by both the Environmental Engineering Laboratory (EEL) and Agrolab, Inc. Agrolab, Inc. analyses included the following: pH, EC, OM%, OM% (LOI at 455 °C), nitrogen species (Nitrate-N, Ammonium-N, Total N), Total P, P Saturation, UMD P FIV, K, Al, B, Ca, Cu, Mg, Mn, Na, S, Zn, Saturations (H%, K%, Ca%, Mg%, Na%). Soil elements were extracted using Mehlich-3 extractant, and the samples were analyzed using Inductively Coupled Plasma Emission Mass Spectroscopy (ICPE-MS).

Soil Analytical Procedures EEL: Prior to chemical testing, all soil samples were oven-dried at 55°C for 72 hours and screened through a 2-mm opening sieve. Table 2 shows soil analyses and related test method information.

Table 2. *Soil Analysis methods, instruments, and lowest standards*

Soil Property	Units	Method	Instrument	Lowest Method Detection Limit
pH		ASTM D4972	VWR symphony B40PCID	-2
EC	μmho/cm		VWR symphony B40PCID	0.001μmho/cm
OM content (LOI at 455 °C)	%	AASHTO T267	Thermonlyne^{TM} Muffle Furnaces	
TC	%	Combustion at 950 °C (infrared detection)	LECO CN628 analyzer, LECO corporation	0.0001%
TN	%	Combustion at 950 °C (thermal conductivity)	LECO CN628 analyzer, LECO corporation	0.0001%
TP, Fe, K and Mg	mg/L	Mehlich-3 extraction	Shimadzu Model ICPE-9820	0.1 mg/L
Ca	mg/L	Mehlich-3 extraction	Shimadzu Model ICPE-9820	1 mg/L
Cu, Mn and Zn	mg/L	Mehlich-3 extraction	Shimadzu Model ICPE-9820	0.01 mg/L

3.5. Analysis of Plant Growth and Nutrient Uptake

Analysis of Percent Coverage: Turfgrass coverage was quantified using digital image analysis (Richardson et al. 2001). Beginning one week after seeding, photos were taken with a Fujifilm X-A7 camera. The camera was set to zero zoom and used autofocus. To ensure consistency across photos, the white balance was set to 5800 with an aspect ratio of 3:2 and a resolution of 4240x2832 which created a 12-megapixel photo. A camera box (48.25 cm x 69.58 cm x 43.81 cm) was constructed out of plywood. A hole (9 cm) was cut on the top to mount the camera at a fixed height above the substrate surface (40 cm). The box blocked interference from outside light and was painted pink on the interior to contrast against natural hues of green, yellow, and brown. The camera was held in place with a ring of foam (2.5 cm thick) to prevent light leakage or camera movement. Two 160 lumen LED lights were mounted on the roof of the camera box to provide consistent light to photograph samples. Each light produced a constant source of 6000K color white light. Photos were analyzed for percent coverage using Turf Analyzer software (Green Research Services, LLC).

Dry Mass Measurements: TS1 vegetation (turfgrass and weeds) was harvested 7 weeks after seeding. Before harvesting turfgrass, weeds were removed by cutting the stem at ground level. Weed shoots were placed in paper bags and dried at 50 °C. After 48 hrs, weed shoot mass was recorded. Turfgrass was cut at the soil surface. It was placed in a paper bag and fresh mass was sent to Agrolab Inc. for tissue analysis. Dry mass was recorded by Agrolab, Inc. To quantify root dry mass, a representative soil core was taken by hammering a galvanized metal cylinder (10.16 cm diameter) through the substrate from top to bottom. Roots were extracted by removing the soil core from the cylinder, placing it over a fine mesh sieve and washing the soil core with a fine-spray hose attachment until no soil remained. Debris was removed and the remaining roots were dried and measured in the same manner described above.

Procedures for plant growth and tissue analyses were identical for TS2 except in the following ways: 1) Weeds were removed in TS2 as they sprouted and 2) destructive analyses were taken 8.5 weeks after seeding.

Tissue Analysis: TS1 and TS2 turfgrass clippings were sent to AgroLab, Inc. for analysis of the following: % N, % P, % K, % Ca, % Mg, % S, % Na, Zn (ppm), Fe (ppm), Mn (ppm), Cu (ppm), B (ppm), Mo (ppm). AgroLab, Inc. digested plant tissue before analyzing for nutrient content on the ICP.

3.6. Analysis of Water Quality Parameters

Tub study water samples (leachate or runoff) were brought to the EEL on the day of each simulated rain event. Samples were measured for pH and Electrical Conductivity (EC) within a few hours. Following this, 200 mL of the sample was filtered through a 0.22 µm membrane for dissolved species analysis. An aliquot of 100 - 300 mL of the sample, depending on the turbidity, was filtered for total suspended solids (TSS) and volatile suspended solids (VSS) measurements (standard method 2540D). For nutrient analysis, unfiltered and filtered samples were stored at 4°C without any acidification because the species were measured within 72 hours of sample collection.

Nitrogen and Carbon: Total nitrogen (TN) and total organic carbon (TOC) were measured on a Shimadzu SSM-5000A Total Organic Carbon/Total Nitrogen Analyzer. A freshly-made glycine stock solution of 1000 ppm was used for building the calibration curve for TN and TOC since glycine's chemical structure contains both N and C. A Dionex ICS-1100 ion chromatograph (ASRS 4 mm suppressor and Dionex IonPac AS22 column) was used for nitrate (NO_3-N) measurements. The ICS is calibrated using a 1000 ppm Nitrate-N standard. Ammonium and Nitrate (NO_2-N) were analyzed on a SEAL AQ300 Discrete Nutrient Analyzer following the salicylate method for ammonia (NH_4-N) quantification. A 1000-ppm Ammonia-N standard solution was prepared using anhydrous ammonium chloride and acidified with 5 N H_2SO_4 in DI water. For NO_2-N, a 500-ppm stock was prepared using dried sodium nitrite in DI water. The lowest MDL for NO_2-N was 0.01 mg/L, NH_4-N was 0.05 mg/L, and for NO_3-N, TN and TOC was 0.1 mg/L. Total Organic Nitrogen was calculated using eqn. 1, assuming that the NO_2-N fraction was negligible in the water samples.

$$\text{TN} = \text{NH}_4\text{-N} + \text{NO}_3\text{-N} + \text{NO}_2\text{-N} + \text{TON} \qquad 1$$

Phosphorus: Aliquots of filtered and unfiltered samples (25 mL) were digested in a HotBlock^{TM} at 100 °C for 40 minutes following the persulfate method (an adaptation of EPA Method 365.1). Digested samples were transferred into 2 mL sample cups for analysis on the SEAL AQ300 for TP and total dissolved phosphorus (TDP). Undigested filtered samples were analyzed to measure OP. Particulate (PP) and dissolved organic phosphorus (DOP) species were calculated using the mass balance eqns. 2 and 3. The lowest MDL for P-species was 0.01 mg/L.

TP = TDP + PP	2
TDP = OP + DOP	3

3.7. Analysis of Soil Physical and Geotechnical Properties

Particle Size Distribution: Soil samples (500 g) were initially wet-sieved through 75µm (#200) sieve. The retained soil and the fines were oven dried at 55 °C for 72 hours. Soil particles >75µm were then subjected to dry sieving as described in the standard method AASHTO T 88 for particle size distribution. The oven-dried fines (<75 µm) were analyzed using a SALD-2300 laser diffraction particle size analyzer. Results from the sieve analysis and laser diffraction were stitched to construct the particle size distribution curve (percent finer vs particle diameter).

Bulk Density: A 10.16 cm (4 in) hollow galvanized steel HVAC duct with a side opening was hammered into each microcosm. The soil core inside each duct represented soil profiles of each replicate microcosm from surface to bottom. The ducts were extracted from the microcosms and placed on plastic trays to prevent loose soil from falling out of the bottom of the ducts. Ducts, soil cores and trays were stored as a unit in 1 gal plastic freezer bags at 2.2 °C until needed. Sampling rings (250 mL) were hammered into the soil cores inside the ducts to measure the soil bulk density of samples. Soil was removed from the sampling rings and dried at 105 °C for 24 hrs. The mass of dry samples was then recorded and used to calculate the bulk density of each sample.

Compaction Tests: The compaction test was performed using the Standard Proctor Test method (ASTM D698). Oven-dried soil samples were prepared at varying water contents in a standard proctor mold (4 in. inner diameter x 4.584 in. height). A 5.5 lb standard compaction hammer was used to compact the soil layers in the mold. The hammer was dropped onto the soil layer from a height of 12 inches for a total of 25 times, generating 12,375 ft-lb/ft^3 of energy. Calculated unit weights (densities) and corresponding moisture contents were plotted and a curve was fitted passing through these data points to determine the optimum moisture content (w_{opt}) and the maximum dry density ($\rho_{d,\,max}$).

Direct Shear Tests: Shear tests were performed per guidelines listed in ASTM 3080. A DigiShear^{TM} Automated Direct Shear System with GeoJac load actuators (Fig. 2) was used to consolidate and shear samples under specified loading conditions. Prior to sample preparation, the oven-dried soils were screened through a 4.75 mm opening sieve. This step was necessary to avoid any interference of larger particles with shear readings and lead to inaccurate results. The soil specimens were compacted at w_{opt} and slightly wetter ($w_{opt+3\%}$) conditions to fit into a shear box of 1 in height and 2.5 in diameter. Three normal loads were chosen for each specimen: 2 psi (low), 7.25 psi (moderate) and 14.5 psi (high). Under these loading conditions, each specimen was consolidated for 24 hours and sheared at a displacement rate of 0.002 inch/min. Shear strength parameters cohesion (c') and friction angle (ϕ) were calculated from the shear plot (shear stress vs normal stress). Shear properties were calculated for both peak and residual shear values to evaluate short- and long-term effects.

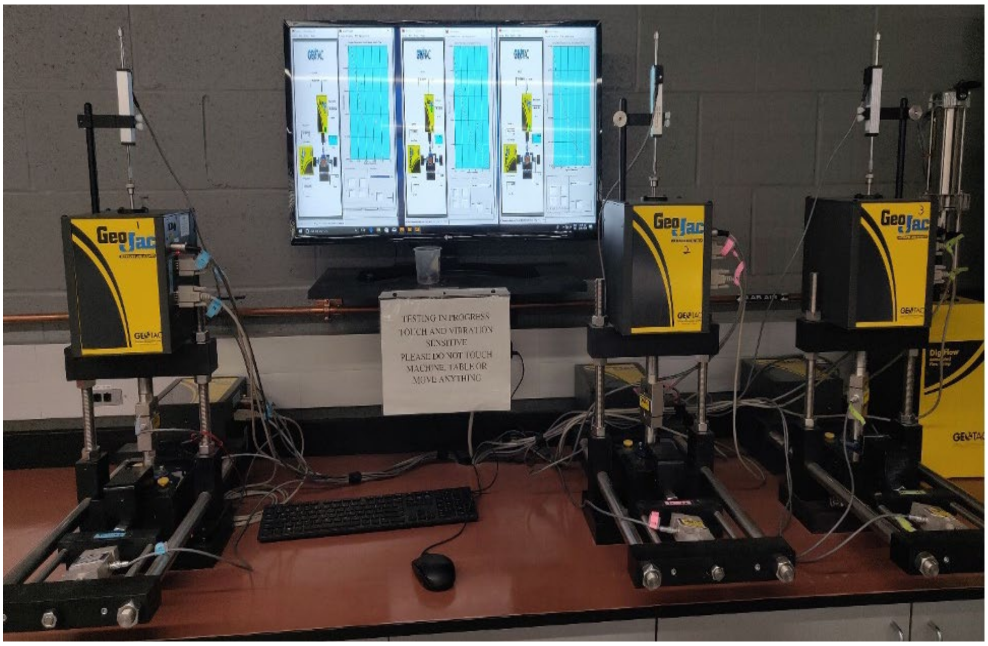


Fig. 2. *Direct Shear Testing for topsoil specimen set under 2 psi (15 kPa), 7.25 psi (50 kPa) and 14.5 psi (100 kPa) stresses.*

Saturated Hydraulic Conductivity Tests:

(a) Flexible-wall permeability: Falling head tests were conducted in Flexible-Wall Permeameters (GEOTAC, TX) as shown in Fig. 3 using the ASTM D5084 test procedure. The specimens (4 in. diameter and 4.584 in. height) were prepared at w_{opt} in the standard proctor mold and transferred into the flex-wall cell slowly without disturbing the compaction conditions. First, the samples were saturated for 7 - 14 days and upon meeting the saturation criteria of $B > 0.95$ as given in ASTM D5084. The samples were then consolidated under an effective stress of 2.9 psi for at least 48 hours prior to taking conductivity readings. The test was terminated upon achieving the criteria of 4 or more determinations to fall within ±25% of a steady state hydraulic conductivity reading.

Fig. 3. *Flexible Wall Permeability Cells*

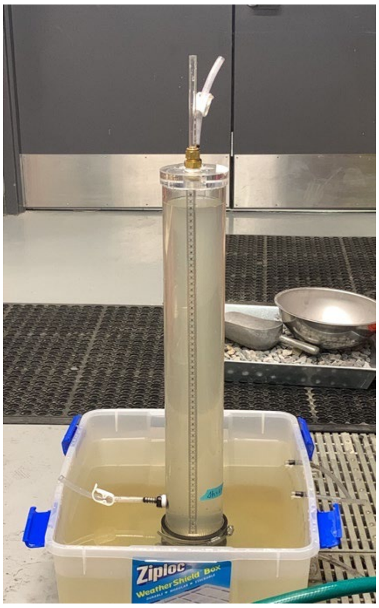


Fig. 4. *Bubble Tube Permeability Apparatus*

(b) Bubble-tube permeability: Constant Head Permeability tests using a GEOTAC Bubble Tub Permeameter (Fig. 4) were conducted to determine the K_{sat} at tub/microcosm soil bulk densities (ρ_d) to mimic tub-soil compaction conditions. Soil cores from the tubs were collected after the growth study was completed to estimate soil ρ_d in the tubs. At these tub-soil densities, test specimens (3 in. diameter and 3 in. height) were prepared in the soil test section of the apparatus. The soil specimen sits on a perforated steel plate which was double-layered with a #100 mesh and the fabric that was used in the tubs, to retain the soil. The experiment was maintained at a constant hydraulic gradient (i) of 0.9 across all the soil samples. Once the sample was saturated, the Mariotte bottle was then filled up to a desired mark and the conductivity readings were taken until 4 or more determinations were within ±25% of a steady state hydraulic conductivity reading.

3.8. Statistics

Where indicated, a one-way analysis of variance (ANOVA) was performed to compare treatment effect on growth measurements, tissue nutrient concentrations, soil nutrient concentrations, and aqueous cumulative sediment/nutrient mass transport. When ANOVA revealed that there was a statistically significant difference on the dependent variable between at least two groups ($F(3, 12) > 3.49$, $p < 0.05$ – except where indicated), post hoc tests using the Bonferroni correction ($\alpha = 0.008$) were performed to determine if pairwise comparisons were significant. When statistical differences are mentioned, treatment means, standard deviations, and p-values are listed within the text or the specified table.

4. RESEARCH FINDINGS

4.1. Soil and Compost Producer Interviews

Contractors are required to submit the intended source of materials for highway construction projects. Submission occurs through a system developed by SHA called the Materials Management System (MMS). MMS data collected by the MDOT Office of Materials Technology (OMT) ranked topsoil producers based on the number of '*Source of Supply'* submissions for each producer in 2019 and 2020. The data do not perfectly depict the number of times each supplier was actually contracted because on rare occasions the supply source can be changed after approval. Reasons for substitutions include out of date nutrient management plans or recent soil test failures. The data also do not quantify the amount of topsoil used in each project but do provide an insight into the topsoil dealers most likely to be used when furnished topsoil is utilized on a construction site. Of the thirteen interview participants, five were ranked in the top ten of intended suppliers and three were ranked in the top five.

All but two survey participants obtained topsoil from sites undergoing development (Question 1). Exceptions included a producer who blends a topsoil-like product from aggregate mining waste and organic materials. The other participant mixes soil delivered by landscape contractors to make SHA specified furnished topsoil. Organic matter is sourced from the materials found in Table 3 (Question 2). The majority of participants prefer to use composted leaf mulch. However due to high costs, demand and seasonal availability of leaf mulch, a combination of organic products is often used. It is important to note that nearly half of the participants (6) reported that they are unlikely to use organic amendments because they prefer to use soil naturally high in OM for SHA jobs. Furthermore, three producers seek and stockpile topsoil that meets furnished topsoil standards to avoid adding OM. Of those unlikely to add OM, all were in the top ten and 2 of the 3 seeking/stockpiling SHA spec soil are in the top five.

Table 3. *Source for organic matter used to amend furnished topsoil*

Source	Number of Producers	Commercial Products*
Composted leaf mulch	8	Leafgro® (Maryland Environmental Service, 4) Soilmate ® (Loudoun Composting, 2)
Wood mulch (sometimes aged)	5	-
Mushroom compost	1	-
Manure	1	-
NA - none used	3	NA

*Manufacturer and number of producers to report are listed parenthesis.

Researchers further explored the major factors that determine the organic materials chosen (Questions 3 & 4). Cost is the predominant factor (reported by 8 producers), followed by product availability (4), quality (4), consideration of SHA furnished topsoil specifications (4), ease of product incorporation (2) and amendment consistency (1). The overall cost of composted leaf mulch varies depending on transportation expenses. Regardless, its availability is inconsistent due to demand. Combined, these factors make it impractical for some producers to consistently use composted leaf mulch to amend soil. On the other hand, wood mulch is widely available and less expensive than leaf mulch. Several soil producers run wood recycling operations. For them, wood mulch is a free source of OM. For others, cheap sources of wood mulch are available since landfill managers offload wood waste at no cost or low costs to save landfill space. In general, but not always, producers shred wood mulch to a fine consistency and age the resulting product before using it as a soil amendment.

To better understand how incorporating organic amendments affects furnished topsoil, researchers asked soil producers to identify the factors taken into consideration when adding OM (Question 4). Considerations with the number of producers reporting each in parentheses include: pH (6), concentration of salts (4), soil texture (3), phosphorus concentration (2), OM content of the amendment (1), effect on infiltration (1), and effect on color (1). Producers were also asked if adding organic amendments to meet the minimum OM concentration (4% by weight) affects other furnished topsoil requirements (Question 7). Keeping in mind that some producers avoid using low OM soil (< 4%), they reported that organic amendments raise pH, raise the concentration of soluble salts, and raise the clay and/or silt content of the soil such that sand must be added to meet the requirements for texture. The number to report such effects were 4, 1, and 4 respectively.

In a research inquiry sparked by these interviews, a UMD undergraduate research intern explored the quarterly soil tests submitted in accordance with SHA Qualified Producer requirements for 2019 – 2021, with guidance from the research team. The objective was to determine if raising the minimum OM concentration to 4% (by weight) for furnished topsoil had an effect on mean OM%, pH, and/or the concentration of soluble salts. Results indicate that mean pH has increased since the 4% rule took full effect at the end of 2019 and fewer producers met the specification for furnished topsoil in subsequent years. A full summary of the quarterly soil test analysis and the full report can be found in Appendix E.

Testing: At the time of the interviews (summer of 2020), SHA used AgroLab Inc. (Harrington, DE) to conduct quarterly soil tests. Researchers asked soil producers about testing protocol during the interviews to investigate whether SHA quarterly soil test results typically met their expectations (Questions 6 & 8). Four producers stated that they were unaware of their results and expressed interest in SHA sharing the results in a timely manner. Nearly half (6) of the producers stated that AgroLab Inc. results did not meet expectations. Low OM results were specifically mentioned by two producers. A majority of the producers (10) primarily use a lab other than AgroLab Inc. for routine testing. Three reported that they use AgroLab Inc. in addition to another lab to better predict whether soil will pass SHA quarterly tests. The independent research project described above compared pH, %OM, and soluble salts results from AgroLab Inc. and OMT over 3 years. A difference in mean pH between labs was found and is described in Appendix E. Additionally, tests performed by the UMD research team were compared to AgroLab Inc. and some differences were noted, particularly in pH, OM%, and soluble salts (EC). UMD researchers believe that this variability could be related to, but not limited to a suspected difference in test procedures, the number of replicates tested for each sample to account for soil heterogeneity, and QA/QC checks.

Biosolids: Only two producers used biosolid OM additions at the time the interviews were conducted. One producer used a composted green-waste product made out of state that includes biosolids when local composted yard waste is not available. The other used biosolids with mulch in topsoil sold for agricultural purposes – not for state highway projects. Five producers expressed interest in biosolids due to availability or low cost. However, concerns about the following kept them from using biosolids at the time: high soluble salts concentration, perception of high pH, potential regulatory requirements associated with transportation and storage, feasibility of onsite storage, odor, and the wet nature of some biosolids which could make them difficult to mix. At least three producers expressed interest in experimenting with biosolids to improve the quality of furnished topsoil if guidance was available.

4.2. Characterization of Maryland Furnished Topsoil Products

Ten furnished topsoil samples were donated by interview participants for analysis by UMD. These samples were stored indoors in 5-gal plastic buckets until processed to determine %OM, pH, soluble salt concentration (SS), cation exchange capacity (CEC), phosphorus content, nitrogen content, and texture (Table 4). Out of the ten topsoils, three samples were unamended (F, H, I); three were amended with leaf-compost (C, D, E); two were amended with finely shredded mulch (A, G); one was amended with mushroom compost (B), and one was amended with a combination of finely shredded mulch and biosolids (J). Except for the sample amended with mushroom compost, every soil fell within the SHA requirement for OM% and soluble salts content when mean with standard deviation is taken into account. The N and P-content for mushroom amended soil was very high (2210 mg-N/kg and 269 mg-P/kg, respectively) compared to others which ranged between 10 – 734 mg-N/kg and 11.87 – 64.03 mg-P/kg. The pH of the soils varied from 6.4 to 7.99, with only one sample meeting the SHA pH spec of 6.1 – 7.2 for furnished topsoil. Each soil met textural (% sand, % silt and % clay) requirements. Parameters that are not listed in the SHA specifications, such as N-content, CEC, and Organic C were analyzed by Agrolab. Inc.

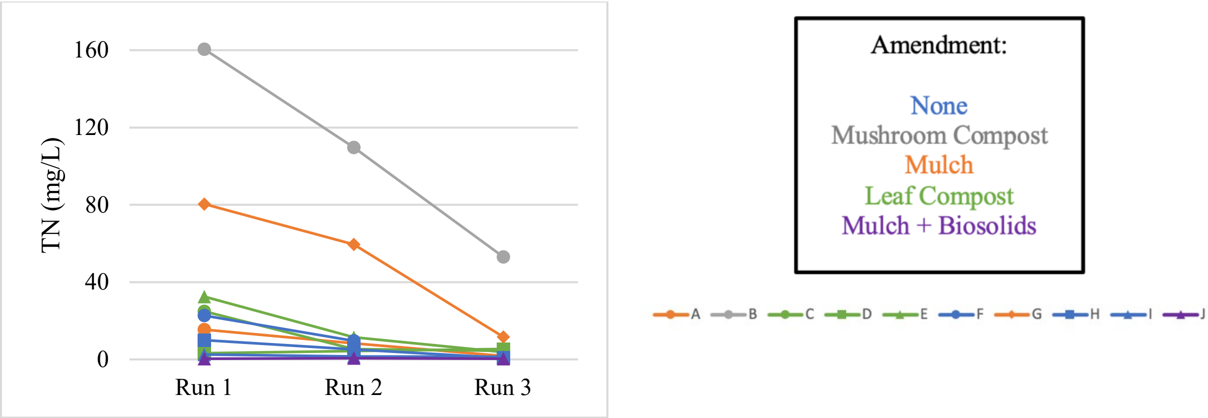
Table 4. *Summary of the ten furnished topsoil samples donated by interview participants.*

Sample ID	Organic Amendment	OM (%)	pH	Soluble Salts (mmhos/cm)	CEC (meq/100g)*	Organic C (%)*	P (ppm)	N (ppm)*	Texture
A	Screened Wood Mulch	3.81 ± 0.35	7.29 ± 0.01	0.49 ± 0.02	10.5	1.83	21.47 ± 0.06	20	Sandy Clay Loam
B	Mushroom Compost	8.93 ± 0.32	7.69 ± 0.05	2.69 ± 0.22	30.4	3.48	269.33 ± 3.79	2210	Silt Loam
C	Soilmate ® (Leaf Compost)	5.89 ± 0.29	7.47 ± 0.14	0.22 ± 0.05	15.5	2.29	22.53 ± 0.21	319	Sandy Clay Loam
D	Leaf compost	6.74 ± 0.16	7.99 ± 0.02	0.23 ± 0.03	16.3	2.61	64.03 ± 0.4	520	Sandy Loam
E	Leafgro ® (Leaf Compost)	5.32 ± 0.28	7.73 ± 0.06	0.21 ± 0.03	11.8	1.86	46.3 ± 0.82	58	Sandy Loam
F	None	3.96 ± 0.12	6.4 ± 0.12	0.25 ± 0.14	8.5	1.44	22.06 ± 0.61	35	Sandy Loam
G	Screened Wood Mulch, Sulfate, and Sand	5.1 ± 0.8	7.46 ± 0.13	0.55 ± 0.12	12.6	1.96	18.67 ± 0.75	45	Sandy Clay Loam
H	None	4.15 ± 0.14	7.5 ± 0.03	0.16 ± 0.03	11.7	1.31	11.87 ± 0.31	10	Silt Loam
I	None	7.44 ± 0.68	7.93 ± 0.06	0.19 ± 0.03	14.2	3.56	34.1 ± 0.17	734	Sandy Loam
J	Screened wood mulch and Bloom ® (possibly manure too)	7.4 ± 0.26	7.62 ± 0.07	0.22 ± 0.01	16.8	2.49	39.1 ± 0.4	551	Sandy Clay Loam

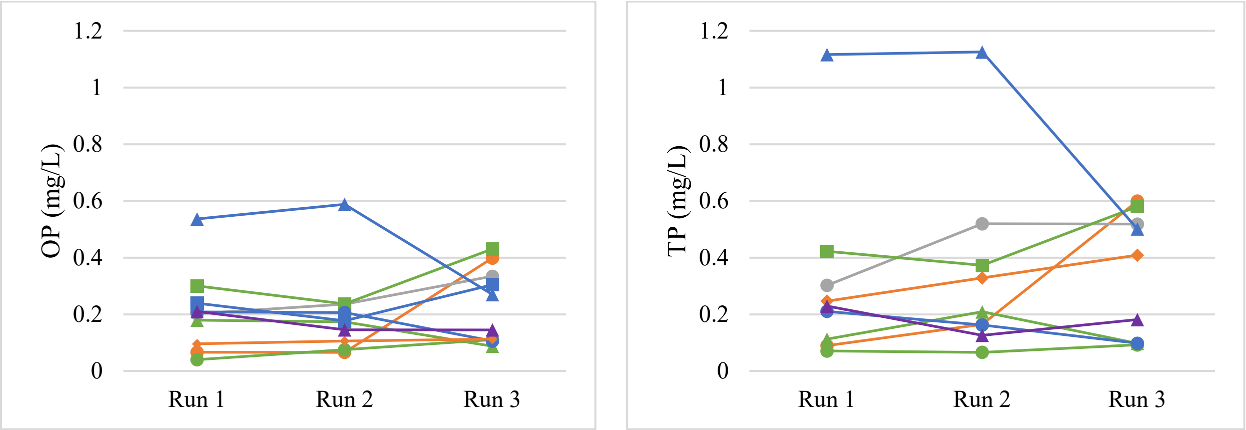
*Processed by Agrolab, Inc. All other results were provided by UMD Environmental Engineering Laboratories.
Notes: All results are expressed as mean or mean ± SD.

4.3. Column Nutrient Leaching Study

Leachates from the column study were analyzed for total nitrogen (TN), total phosphorus (TP), and ortho-P (OP). Concentration averages for TN, TP, and OP are summarized in Fig. 5a-c, while the mass losses of TP and TN are provided in Fig. 5d and Fig. 5e. Leachate results for the first run represent drainage from a 5.08 cm simulated rainfall event (2 in of DI water). A comparison of TP and OP concentrations in the first run leachate is given in Fig. 6. Average concentrations for the first run are reported since the moisture content of the soil differed between samples, which affected leachate volume. Thus, mass loss (concentration x volume) for the first run is not reported. Rather, mass loss for all three runs is shown since each sample was fully saturated after the first run.



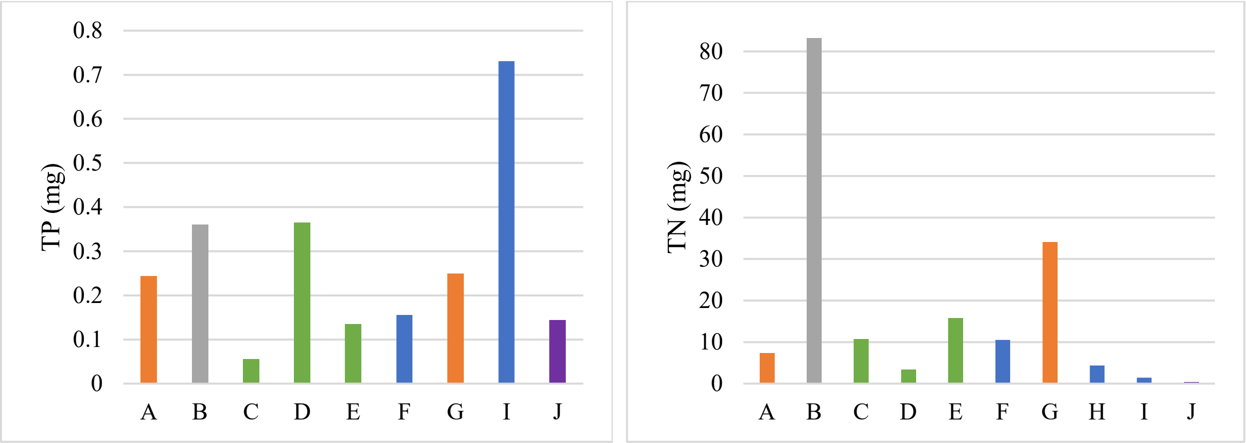
(a) Column Study Leachate Concentration Averages for TN (mg/L)



Note: Data not available for H

(b) Column Study Leachate Concentration Averages for OP (mg/L)

(c) Column Study Leachate Concentration Averages for TP Concentrations (mg/L)



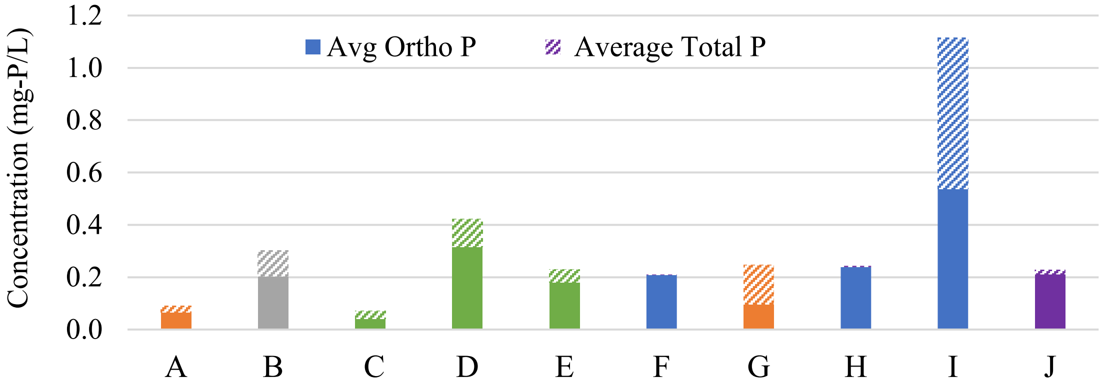
Note: Results based on run averages

Note: Results are based on run averages

(d) Average Mass Loss of TP (mg)

(e) Average Mass Loss of TN (mg)

Fig. 5. *Summary of Concentration Averaged for TN, TP and OP, and mass losses for TP and TN*



Note that Total P results were not calculated for sample H due to sampling errors.

Fig. 6. *Average concentration of Ortho P and Total P in first run leachate of the column study*

The relationships between amendments and nutrient leaching patterns were not clear based on the results of the column study. Producers did not report the rates at which amendments were incorporated. Without knowing incorporation rates, deciphering the results was difficult for the researchers. Soil test results offer some clues but do not explain the results entirely. For example, sample B (amended with mushroom compost) had the highest concentration of TN in the soil (2210 ppm) and the highest mass loss of TN via leachate. However, sample G (amended with mulch) lost more than 2 times more TN than the remaining 8 samples and had a soil concentration of only 45 ppm. On the other hand, samples D, I, and J had the lowest leachate concentrations despite having over 500 ppm of soil TN. Excluding samples B and G, all other samples lost on average less than 16 mg of TN after 10.16 cm (4 in) of DI water was applied to the columns. Sample J, amended with biosolids and mulch, lost the least amount of TN on average (0.38 mg). The standard deviation for TN run averages for sample G were high (Run 1: average = 80.41 mg/L, S.D. = 13.34; Run 2: average = 59.46 mg/L, S.D. = 28.26; Run 3: average = 11.66, S.D. = 10.27), which suggests that the soil was not homogenous. This could explain why soil TN was low compared to leachate TN but it does not explain why higher TN values were not seen in the leachate from samples D, I, and J, which had high soil concentrations.

Reconciling soil P analysis results with leachate P results was also difficult. Sample I had the greatest concentration of OP and TP in the leachate, followed by samples D and B. The average mass loss of TP from I (0.73 mg) was more than double the averages for samples B and D (approximately 0.36 mg each). Sample I was not amended but B and D were with mushroom compost and leaf compost, respectively. The amount of OP to TP was comparable for most samples meaning that the majority of P in leachate was dissolved in an inorganic form. The exception was sample I, in which half of the TP was associated either organic P and/or P bound to sediment. Fine filters (1.6 μm) were used in the column study; therefore, the majority of P in sample I was likely organic-P, since the filters would have removed much of the fine sediment in the leachate. Using a Mehlich III extraction, samples B and D had high concentrations of P in the soil (269 ppm and 64 ppm, respectively), while sample I had 34 ppm, considered average.

Note that a high P sufficiency level for turfgrass establishment is > 55 ppm and 27 - 54 ppm defines the medium sufficiency level (Carrow et al. 2001c). Higher P losses from samples

D and I may be explained by their texture - sandy loam. (Wyatt et al. 2017). It is well established that sandy soils are more susceptible to leaching and thus nitrate losses. There is also evidence that texture plays a significant role in P losses through leaching. Sandy soils, especially those with low CEC or high dissolved organic phosphorus that exceed the adsorption capacity of the soil, are known to leach higher volumes of P than other soils. For example, Djodjic et al. (2004) investigated P leaching in relation to soil type and soil P. These researchers did not identify a correlation between leachate concentrations and soil P values. Rather, they found that the water transport mechanism through soil was a more important factor for determining P losses than soil P concentrations. They concluded that site-specific factors may be better indicators for potential P losses via leaching since a single general indicator for all soil types was not apparent. Gerhard et al. (2021) studied P leaching from naturally structured forest soils and also identified texture to be an important predictor of P losses along with soil organic carbon content. They concluded that the release of P was best explained by the solubilization of organic carbon which was thought to mobilize organic P. It should be noted that samples B, D, and I had the three highest measures of organic carbon.

The column study highlights that predicting amendment effects on N and P leachate losses will be a challenge unless very specific soil characteristics are known and exceed the parameters investigated in the column study. Even so, a soil TN test and organic carbon test can offer insights to the potential loss of N and P through leaching. For example, soil TN includes organic N, which can be mineralized over time and is overlooked by most soil fertility tests which focus on nitrate and ammonium. A soil TN test should not be used for fertilizer recommendations, but it can reveal the capacity of soil to supply nitrate. Soil TN interpretations are limited, but a study conducted by Zhao and Xia (2012) could provide a benchmark for landscape managers to consider. The researchers calculated a soil TN mean of 753.84 mg/kg (ppm) after examining the concentration and spatial distribution of soil TN across various land use areas. The soil TN concentration for sample B was nearly three times higher than the average determined by Zhao and Xia (2012). With regard to P losses, surface runoff is the primary concern since P mobility is generally limited in soil. However, the column study showed that organic P can leach in concentrations that exceed typical stormwater TP concentrations seen along highways 0.25 - 0.45 mg/L (“Minnesota Stormwater Manual” 2021). Limiting the amount of sand in SHA furnished topsoil could reduce nitrate losses and possibly TP losses in sandy soil with high organic C.

4.4. Tub Study Soil Characterization

Furnished Topsoil Standards: Tub Study 1 (TS1) and Tub Study 2 (TS2) treatments were compared to SHA furnished topsoil standards to determine if the control soil and amended soils complied with furnished topsoil specifications for pH, % OM, maximum soluble salt concentration, % sand, % silt and % clay. Each TS1 and TS2 soil met % OM, % sand, % silt, and % clay specifications. Additionally, each TS1 soil was within the specified pH range (6.1 - 7.2) at the beginning of the experiment. However, BAT1 did not meet the minimum pH standard by the end of the experiment. In TS2, MAT2 exceeded the pH range at the beginning of the experiment. By the end of the experiment, CUT2, MAT2, and LAT2 exceed the pH range. Finally, both BAT treatments and MAT1 exceeded the SS limit (0.78 mmhos/cm) at the beginning of the study. For all, the concentration fell by the end of the experiment but only BAT2 was under the specified limit.

Soil Bulk Density: Bulk density was measured at the end of the experiment. Significant differences were not found in TS1 treatment means, which were 1.16 ± 0.08, 1.18 ± 0.07, 1.31

± 0.10, and 1.21 ± 0.04 g/cm^3 for CUT1, MAT1, LAT1, and BAT1 respectively. TS2 mean densities were 1.21 ± 0.03, 1.4 ± 0.04, 1.21 ± 0.04, and 1.21 ± 0.07 g/cm^3 for CUT2, MAT2, LAT2, and BAT2, respectively. CUT2 and MAT2 were significantly different (F(3,8) = 8.73, p = 0.007). However, bulk density across treatments and studies were ideal for sandy and silt loams and likely would not have restricted root growth ("Bulk Density" 2008). Soil physical and chemical properties are summarized in Table 5 and Table 6.

Summary of Soil Fertility Concerns for Vegetation Establishment:

CUT1: High C:N, low P
MAT1: High EC, high C:N, low P
LAT1: Low P
BAT1: High EC, low pH, low C:N, high TN

CUT2: High pH, low P
MAT2: High pH, high C:N, low P
LAT2: High pH
BAT2: High EC, low pH, low C:N, high TN

The soil matrix is highly dynamic and depends on complex physical, chemical, and biological micro and macro interactions. Soil tests can inform of potential nutrient deficiencies but do not necessarily reflect the sufficiency of plant uptake. Therefore, the soil fertility concerns highlighted above will be discussed along with the tissue analysis and growth measurements in Section 4.7.

Table 5. *Tub Study 1 soil fertility summary. Treatments included an unamended topsoil (CUT1), a soil amended with mulch (MAT1), a soil amended with leaf compost (LAT1), and a soil amended with biosolids (BAT1).*

	CUT1 Sandy Loam		MAT1 Sandy Loam		LAT1 Silt Loam		BAT1 Sandy Loam	
Measurement	Before	After	Before	After	Before	After	Before	After
% OM (LOI)	7.2	6.4	6.32	5.86	6.03	6.25	5.76	6.56
EC (mmho/cm)	0.59	0.3	1.37	0.79	70.8	0.47	2.16	0.94
pH (1:1)	6.7	6.87	6.57	6.93	6.78	7.01	6.19	5.2
CEC (meq/100g) *	11.3	11.1	12.9	10.9	13.9	14.9	9.4	13
mg-C/kg	31980	29774	30215	24402	29000	31049	26662	29257
mg-N/kg	1242	1687	1628	1501	1958	1875	3956	3661
C:N ratio	25:1	18:1	19:1	16:1	15:1	17:1	7:1	8:1
mg-P/kg*	26	**23**	**15**	**17**	**20**	26	92	146
mg-K/kg*	137	139	158	140	126	142	188	174
mg-Ca/kg*	1834	1818	2171	1843	1993	2145	1311	1341
mg-Mg/kg*	153	143	126	111	378	386	181	200
mg-Fe/kg	507	512	339	441	406	429	850	704
mg-Mn/kg	94	39	280	264	109	103	84	82
mg-Cu/kg	5.5	1.6	4.6	3.8	5.4	4.1	5.2	4.3

Notes: All results are expressed as means. Values that fall outside of furnished topsoil specifications are underlined. Low sufficiency ratings are indicated with boldface type.
* Determined by AgroLab, Inc.

Table 6. *Tub Study 2 soil fertility. Treatments included an unamended control soil (CUT2) and soil amended with mulch (MAT2), leaf compost (LAT2), or biosolids (BAT2).*

	CUT2 Silt Loam		**MAT2** Silt Loam		**LAT2** Silt Loam		**BAT2** Silt Loam	
Measurement	Before	After	Before	After	Before	After	Before	After
% OM (LOI)	4.34	3.99	6.86	5.41	5.92	5.06	5.64	5.1
EC (mmho/cm)	0.3	0.28	0.28	0.37	0.59	0.34	1.89	0.57
pH (1:1)	7.21	7.55	7.31	7.52	7.18	7.55	6.79	7.21
CEC (meq/100g) *	13.3	11.2	15	12.4	18.1	12.7	15.5	13.7
mg-C/kg	15522	15923	29631	25360	25901	22414	22868	23411
mg-N/kg	1386	1394	1460	1664	2223	1919	2935	2553
C:N ratio	11:1	11:1	20:1	15:1	12:1	12:1	8:1	9:1
mg-P/kg *	**15**	**14**	**16**	**13**	41	**23**	37	42
mg-K/kg *	127	104	145	122	286	176	162	85
mg-Ca/kg	2162	1965	2412	2242	2483	2303	2681	2141
mg-Mg/kg	143	127	153	161	206	188	196	159
mg-Fe/kg	394	351	438	451	533	398	577	452
mg-Mn/kg	335	326	355	359	353	334	257	267
mg-Cu/kg *	3.1	2.6	3.1	2.5	3.2	2.7	4.0	4.9
mg-B/kg *	0.85	0.62	0.98	0.69	1.23	0.93	0.99	0.75
mg-S/kg *	40	17	35	10	41	12	149	59

Notes: All results are expressed as means. Values that fall outside of furnished topsoil specifications are underlined. Low sufficiency ratings are indicated with boldface type.
* Determined by AgroLab, Inc.

4.5. Tub Study Geotechnical Tests

Particle Size Distribution: SHA standards for sand, silt and clay are Sand: 20 – 75 %, Silt: a maximum of 75%, Clay: a maximum of 30%, and a minimum of Silt + Clay: 25%. The PSD of TS1 and TS2 soils fall within the above specifications of SHA furnished topsoil (Table 7). LAT1 had the greatest amount of fines content (< 0.075 mm) at 65%, with BAT2 contributing to the lowest at 51.5%. USDA soil textural analysis revealed that the TS1 soils fall in the category of sandy loam, with an exception to LAT1 which was classified as a silt loam. Addition of organic amendments to TS2 control soil (CUT2), showed a slight increase in the silt fraction and thereby decreasing the sand fraction of the amended soils. The clay content of the TS2 soils was comparable as can be expected because the organic amendments typically do not contribute to the addition of clay particles to the topsoil. All the TS2 soils were classified as silt loam, and in spec with that of SHA standards. Additionally, the variability in TS2 soils for fines or gravel content was minimal (Fig. 7) given that the same control soil was used across the board, with only an adequate addition of OM in order to meet the SHA spec of 4 – 8 %.

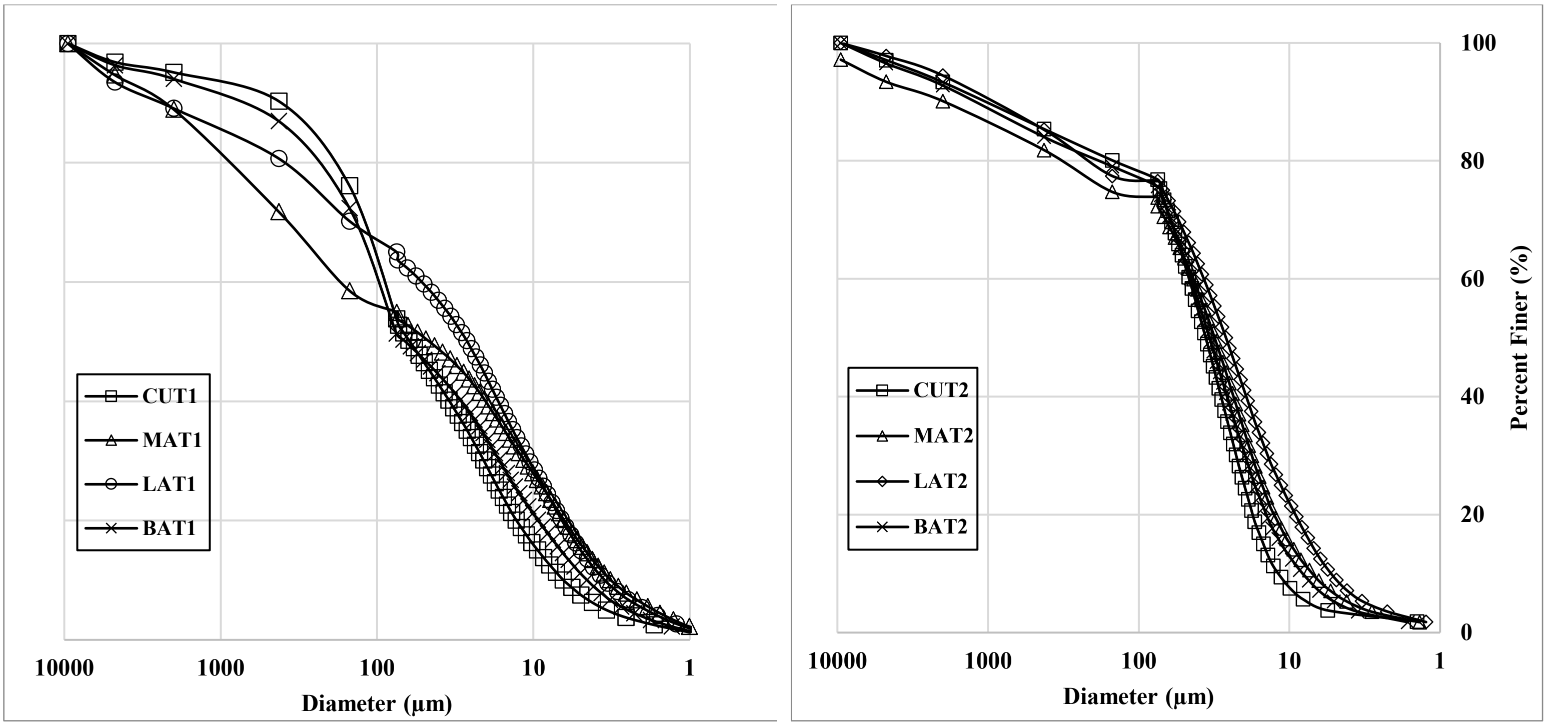


Fig. 7. *Grain Size Distribution of the tub study soils (TS1 and TS2)*

Table 7. *USDA soil classification of the tub study soils (TS1 and TS2)*

Soil	***Sand (%)***	***Silt (%)***	***Clay (%)***	***Texture***
CUT1	53.5	44	2.5	Sandy Loam
MAT1	50.6	43.8	5.6	Sandy Loam
LAT1	41.7	54.2	4.1	Silt Loam
BAT1	53	43.6	3.4	Sandy Loam
CUT2	37.9	60.2	1.9	Silt Loam
MAT2	36.2	62	1.8	Silt Loam
LAT2	33.9	64.3	1.8	Silt Loam
BAT2	36.2	62.1	1.8	Silt Loam

Compaction Characteristics: Table 8 below shows the compaction characteristics of TS1 and TS2 soils. Soil organic matter plays an important role in the inherent characteristics of maximum dry unit weight ($\gamma_{d,\ max}$) and moisture content (w_{opt}) of soils. Organic amendments, given their aggregate nature, lower bulk densities and higher water retention abilities, tend to drive down the maximum dry unit weight of soil (Kranz et al. 2020). This effect can be observed in the treatments of TS2 soils, where addition of mulch, leaf compost, and biosolids, lowered the max unit weights. This trend stayed consistent even with the TS1 soils, where the amended soils (MAT1, LAT1, BAT1) showed lower $\gamma_{d,\ max}$ when compared to the respective control soil (CUT1).

Table 8. *Compaction properties of the tub study soils (TS1 and TS2)*

	Tub Study 1 Soils				**Tub Study 2 Soils**			
Property	*CUT1*	*MAT1*	*LAT1*	*BAT1*	*CUT2*	*MAT2*	*LAT2*	*BAT2*
Maximum Dry Unit Weight ($\gamma_{d, max}$) (lb/ft^3)	106	99.6	102.2	98.4	101.8	96.4	98.8	98.8
Optimum Water Content (w_{opt}) (%)	16	18	15.5	19.5	18	20	16.5	18

Direct Shear Tests: Results of the direct shear experiments are presented in Appendix C (Fig. S2 and Fig. S3). It can be noticed in these Mohr-Columb failure envelopes that an increase in vertical stress translated to an increase in the peak shear stress values of the soil samples. With the addition of organic amendments, the effective cohesion (c’) of the soils slightly improved compared to CUT2, following the order of BAT2 (2 psi) > MAT2 (1.6 psi) > LAT2 (1 psi) > CUT2 (0.9 psi). On the contrary, the effective friction angle (ϕ’) of the amended treatments was lower than the control soil (CUT2) and ranged from 32.5° – 40.4°. A recent study (Duzgun et al. 2021) that tested shear properties of compost amended topsoils, observed an increase in both effective friction angle and cohesion with compost addition. Although this trend conforms with the c’ results of this study, it deviated from that of the friction angle (ϕ’). The difference in the application rates of amendments, compost type, and base soil properties between the two research studies could have contributed to this change in trend. Additionally, an absence of fibrous elements in that of the amended soils could have impacted the friction angle. Per TS1, although the soils are distinct in their properties, the effective cohesion was more for the amended soils compared to CUT1, and vice-versa with respect to the friction angles.

Additionally, to better under the variability in strength properties under wetter conditions, the study tested TS1 and TS2 soils at compaction conditions of $w_{opt+3\%}$. As can be observed in the Mohr-Coulomb plots Fig. S2 and Fig. S3, treatments under $w_{opt+3\%}$ showed a decline in the c’ values compared to the ones compacted at w_{opt}. This difference was the highest seen in BAT2 (w_{opt} - $w_{opt+3\%}$ = 1 psi), followed by LAT1 (w_{opt} - $w_{opt+3\%}$ = 0.8 psi), and the least was MAT1 and CUT2 (w_{opt} - $w_{opt+3\%}$ = 0.1 psi).

Table 9. *Shear properties from Direct Shear testing of the tub study soils (TS1 and TS2)*

Shear Properties	***At optimum water content (w_{opt})***				***At optimum water content + 3% ($w_{opt+3\%}$)***			
	CUT1	*MAT1*	*LAT1*	*BAT1*	*CUT1*	*MAT1*	*LAT1*	*BAT1*
c’	0.6 (4.1)	1.4 (9.7)	1.1 (7.6)	1.6 (11)	0.3 (2.1)	1.3 (9)	0.3 (2.1)	1.1 (7.6)
ϕ’	38.2°	36.9°	35.2°	32.5°	35.1°	34.1°	37.7°	35.5°
	CUT2	*MAT2*	*LAT2*	*BAT2*	*CUT2*	*MAT2*	*LAT2*	*BAT2*
c’	0.9 (6.2)	1.6 (11)	1.0 (6.9)	2.0 (13.8)	0.8 (5.5)	1.3 (9)	0.3 (2.1)	1.0 (6.9)
ϕ’	40.4°	36.6°	38°	32.5°	34.8°	35.2°	37°	32.8°

c’: effective cohesion with units presented in psi (kPa) and ϕ’: effective friction angle in degrees (°)

Similarly, wetter compactions decreased the friction angles across all the treatments, with an exception to BAT2 (w_{opt} = 32.5° and $w_{opt+3\%}$ = 32.8°). This occurs because as the water content increases, the cohesion forces between the soil particles decrease as the moisture occupies the void spaces in the soil matrix. All in all, the shear parameters (low c' values) indicated that the TS1 and TS2 soils align with that of the earthen materials, and not clays. From the strength perspective, it could be concluded that addition of organic amendments has shown to improve the soil structure and can hence be recommended for use on highway slopes.

Saturated Hydraulic Conductivity: Table 10 provides information on saturated hydraulic conductivities (K_{sat}) of TS1 and TS2 materials at their corresponding optimum water contents. K_{sat} values were estimated after a steady flow-through state of water through the soils was achieved under saturated conditions. Out of the TS1 soils, $K_{sat,}$ at w_{opt} values indicated that MAT1 has the highest permeability (by ~an order of magnitude), followed by BAT1 > LAT1 > CUT1. The K_{sat} of the soil counterparts in TS2 varied within the range of $1.19 – 7.49 \times 10^{-7}$ cm/s, again with MAT2 exhibiting better saturated conductivity traits. Organic amendments increase the K_{sat} of the CUT2 soil, by 4.7 times in MAT2 and 3.4 times higher in LAT2. However, K_{sat} of BAT2 was comparable to that of CUT2.

Table 10. *Summary of Saturated Conductivities of the tub study soils (TS1 and TS2)*

Tub Study Soil	*K_{sat} (at $\gamma_{d, max}$) (cm/s)*	*K_{sat} (at γ_{tub}) (cm/s)*
CUT1	8.01×10^{-8}	2.39×10^{-3}
MAT1	5.08×10^{-6}	8.92×10^{-3}
LAT1	2.35×10^{-7}	1.60×10^{-3}
BAT1	2.93×10^{-7}	6.49×10^{-3}
CUT2	1.61×10^{-7}	1.78×10^{-3}
MAT2	7.49×10^{-7}	3.57×10^{-3}
LAT2	5.43×10^{-7}	2.54×10^{-3}
BAT2	1.19×10^{-7}	2.14×10^{-3}

K_{sat}: Saturated Hydraulic Conductivity at maximum dry unit weight ($\gamma_{d, max}$) and at bulk densities in tubs of the soils.

A difference of 3 – 5 orders of magnitude is noted between the soils compacted at their maximum dry density and at tub bulk density. This can be expected given the loose packing of soils, allowing a freer movement of water through the soil matrix even under saturated conditions. Among the TS1 soils, LAT1 exhibit the lowest K_{sat}. This may be owed to the highest fines content of LAT1 compared to others. Both MAT1 and MAT2 outperform the soils in their respective study sets. Aged mulch is known to contribute to increased soil pores, thereby improved conductivity. In general, addition of compost or compost-like materials increased soil void ratio. As a result, the unit weight or density decreased, and conductivity increased. Results from this research are in line with the results of other studies, where compost additions enhanced the saturated hydraulic conductivity (Duzgun et al. 2021; Cannavo et al. 2014; Olson et al. 2013; Bhatt and Khera 2006).

4.6. Tub Study Leachate / Runoff Analysis

4.6.1. Volume

A total of eight simulated rain events were applied to all treatments on a weekly basis during the TS1 experiment. All four treatments including all replicates (n=4) produced leachate from each rain event. Additionally, LAT1s discharged surface runoff in some weeks, but not necessarily from all replicates. An observation was made when determining the saturated hydraulic conductivities (K_{sat}) of LAT1, that the LAT1 soil took longer to saturate and had the lowest K_{sat} under tub bulk density given its higher fines content, compared to other TS1 treatments (Section 4.4). This could mean that this particular soil when subjected to the wetting/drying cycles (temperature effects) experienced in TS1, impacted the degree of saturation (soil moisture content) and therefore dictated the water flow-through conditions. Replicates provided consistent results in the CUT1, MAT1 and BAT1 blends. TS2 had 9 simulated rain events. CUT2 and LAT2 treatments observed runoff in the later rain events (#7, #8, #9) of TS2, but not in measurable quantities. Leachate was collected from all the TS2 tubs and rain events. Additionally, the quantity of cumulative leachate exiting the tubs from rainfall event 1 through 9 was not significantly different ($p > 0.05$) across treatments (and replicates). Since the tubs were constructed on an incline of 4% (25:1 engineering slope), the slope was not steep enough to discharge significant surface runoff.

4.6.2. Water Quality

Water quality analyses were performed for all leachate and runoff samples from rain events 1 through 8, except for rain event 7. TP and TN concentrations in storm 7 leachate were estimated by taking the mean of the concentrations quantified from storm 6 and storm 8 leachates. As for TS2, a total of 9 rain events were applied, of which the TP and TN were measured for all the rain events, and the remainder of the water quality parameters were analysed for all storms except 7 and 9. Sediment/Nutrient Mass transport from each replicate was calculated by multiplying the concentration by the collected volume, and normalizing this with the volume of tub soil (mg / ft^3). Cumulative Mass Transport (CMT) was calculated by summing the individual mass transports for each replicate across total applied rain events.

Sediment Transport: Fig. 8 shows the cumulative sediment mass transport from TS1 and TS2 treatments. Among the TS1 soils, LAT1 had more sediment runoff compared to others, with BAT1 having the least. Total suspended solids (TSS) concentrations of LAT1 treatments followed no apparent trend with successive storms; however, CUT1, MAT1 and BAT1 showed a decline from 63.5 to 29.8 mg/L TSS, 51.3 to 11.2 mg/L TSS and 67.1 to 7.8 mg/LTSS respectively (Fig. S1a, Appendix C). The highest recorded average concentration (±SD) for LAT1 was 2116 ± 2322 mg/L TSS (storm 1) and the lowest was 143.8 ± 59.8 mg/L TSS (storm 4). The high standard deviation resulted from a high TSS value in one LAT1 replicate which adds to the prior discussion about volume irregularities.

No discernible trend was seen in the TSS mean concentrations of the TS2 soils as time progressed (Fig. S1b, Appendix C). However, the addition of organic amendments (mulch, leaf compost and biosolids) to the TS2 control (CUT2) led to lower overall sediment export through leachate by 665 mg/ft^3, 398 mg/ft^3, 811 mg/ft^3 from MAT2, LAT2 and BAT2 respectively. Given the complexity of sediment transport through soils, estimating TSS concentrations for the excluded storms (#7 in TS1, #7 and #9 in TS2) for each treatment could not be done, and so the calculated CMT values should be regarded as underestimates for total sediment mass loss.

TSS is an important measure in the context of stormwater management. Water quality issues in leachate can likely carry over into stormwater discharges and impair water bodies. The inorganic fraction of the sediment has the potential to tie up phosphorus (given the presence of oxide minerals) and the organic fraction can accumulate and transport toxic metals and other organic pollutants (Cao et al. 2019; Zgheib et al. 2011; Herngren et al. 2005). The national median of stormwater TSS event mean concentrations (EMC) originating from the US urban regions is 47 mg/L TSS (N = 8530) (Pamuru et al. 2022). Of the eight soils used in TS1 and TS2, LAT1 was the only treatment that exceeded typical urban TSS levels owing to its fines content.

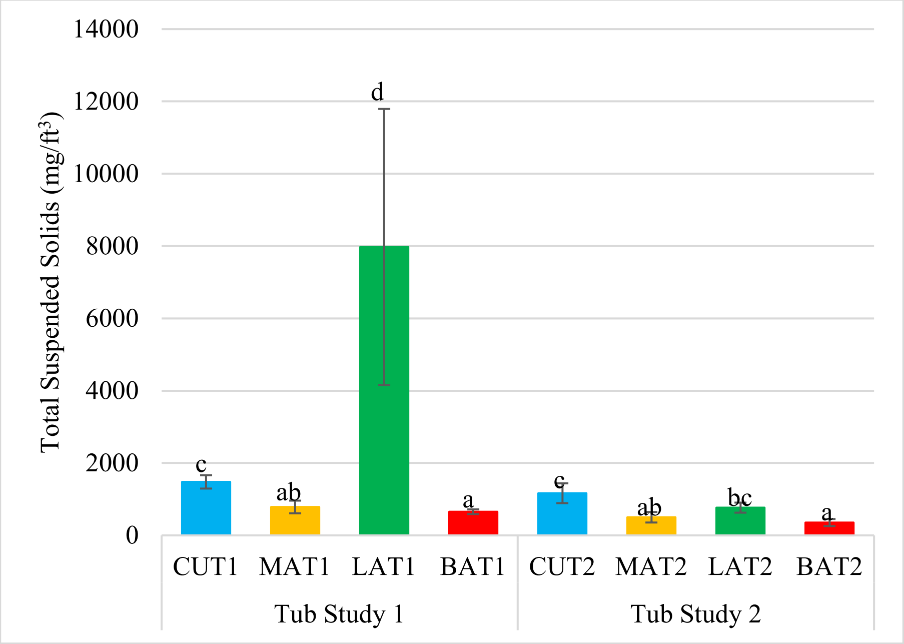
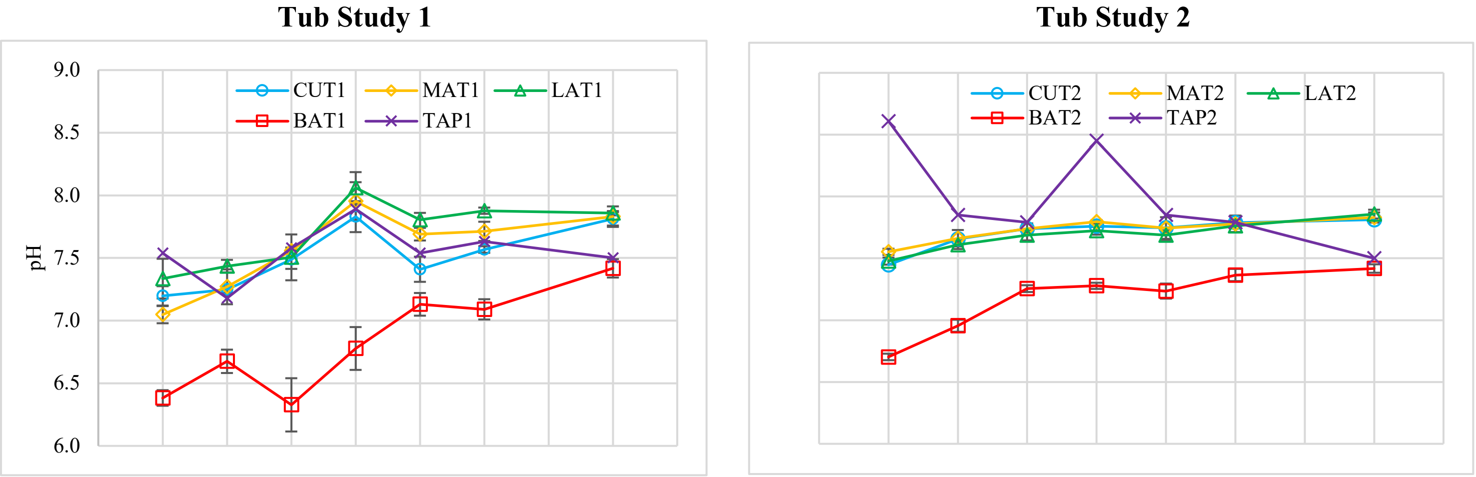


Fig. 8. *Average of cumulative mass transport of sediment (n=4) from treatments used in Tub Study 1 (TS1) and Tub Study 2 (TS2). Note: means with the same letters indicate no significant differences at a 95% confidence level.*

General Water Quality Parameters: Fig. 9 shows the trends of the four-replicate average pH, EC and TOC for each treatment in the collected leachate samples from TS1 and TS2. Since a 1-inch rainfall was simulated each week, the x-axis of the concentrations/mass transport plots can be equally well interpreted as the applied rainfall (in inches) and also the ordinality of the rain events.

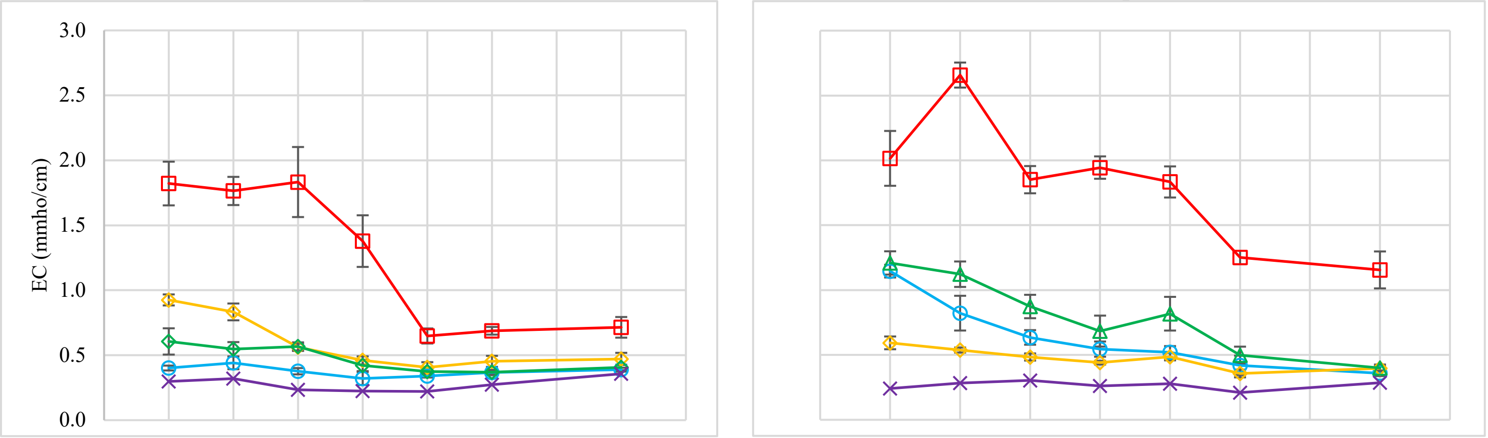
As observed in the soil analysis, addition of biosolids (which is high in NH_4-N and organic N) lowered the pH of the base soil(s) in both growth studies (TS1 and TS2) as a result of ammonification (conversion of organic N to NH_4-N) and nitrification (conversion of NH_4-N to NO_3-N). A similar trend was noted in the leachate samples where BAT1 and BAT2 were slightly acidic compared to the other treatments in the respective studies. In TS1, a clear increase in the pH levels across all treatments was noted over time. In TS2, this trend was observed only in the BAT2 treatment, while the pH of CUT2, MAT2 and LAT2 only increased by <0.4 pH units between rainfall events 1 and 8, regardless of the fluctuations noticed in the tap water pH itself. Changes in pH can be attributed to plant uptake of nitrate and ammonium. Soil acidity is reduced as the biomass increases because plants release organic carboxyl ions (which increases soil pH over time) as they take up various anions (Guan 2016). However, an accumulation of H^+ ions can reduce the rhizosphere soil pH when nitrate plant uptake needs are met.

Leachate soluble salt concentrations (EC) opposed pH trends. A clear decline in EC, followed by steady concentrations were observed in most treatments between TS1 and TS2. This trend was least pronounced in CUT1, LAT1 and MAT2 soils, given that their soil EC was already low to begin with. TS2 soils showed that leaf compost and biosolid amendments increased total EC compared to the control soil in the leachate, while mulch reduced it. BAT treatments showed significantly higher EC values overall, compared to CUT, MAT and LAT within the two studies, because of BATs high initial soluble salt content. The presence of ions such as sulfate, chloride and sodium in biosolids cause an increase in soil EC (Pinto et al. 2018). One of the effective strategies in reducing the salt content is through soil leaching (FAO 1988). This effect was shown in both studies, where EC concentrations (i.e. salts) were reduced by subsequent rainfall events.



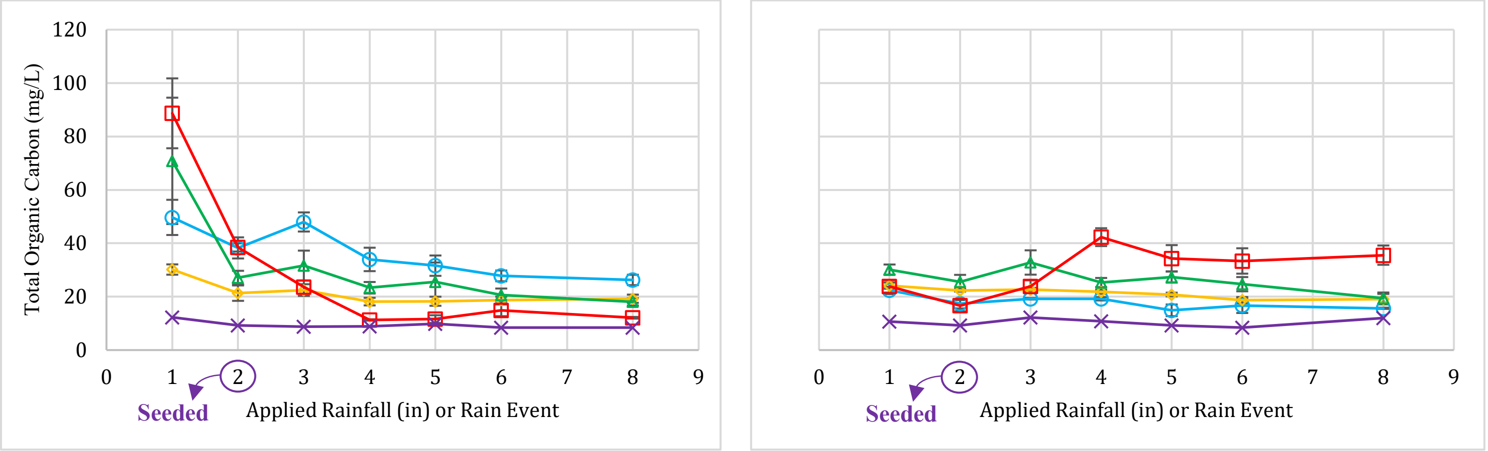
(a) pH

(b) pH



(c) Electrical Conductivity

(d) Electrical Conductivity



(e) Total Organic Carbon

(f) Total Organic Carbon

Fig. 9. *pH, Electrical Conducitivity (EC) and Total Organic Carbon (TOC) in leachate samples collected from Tub Study 1 (**a, c** and **e**) and Tub Study 2 (**b, d** and **f**) treatments.*

Total Organic Carbon (TOC) in TS1 leachate samples peaked during rainfall event 1 followed with a sharp decline in rainfall event 2; thereafter, TOC gradually decreased and levelled out over time. By the end of the study, BAT1 declined to concentrations lower than other treatments, even though it exported the highest amounts at the onset of the rainfall applications, when the biosolids amendment was newly incorporated. As nitrification increases in soils, leachable organic C tends to decrease, which is why a downward temporal trend was observed (O'Keeffe and Akunna 2022). In TS2, even after the application of organic amendments, the TOC losses were within the range of 14.9 and 42.3 mg/L across all treatments, compared to the range of 8.43 – 88.7 mg/L in TS1. Additionally, higher TOC leached from amended soils compared to the control soil (CUT2) throughout the study. Although a gradual decrease in organic carbon concentrations were noticed in the TS1 treatments, three of the TS2 treatments (CUT2, MAT2 and LAT2), BAT2 performed differently. The BAT2 leachate concentrations rose to its highest mean (42.3 mg/L) after the 4th rainfall, later dropped and plateaued in the successive storms at 35.6 mg/L (storm 8), still greater than 19.4 mg/L, 19.1 mg/L, 15.7 mg/L for LAT2, MAT2, and CUT2 respectively. Parameters such as soil pH, C:N ratio, compost maturity can be critical in assessing the organic C leaching from soils (O'Keeffe and Akunna 2022; Toribio and Romanyà 2006; Zmora-Nahum et al. 2005). Typically, basic soils, with lower C:N ratio amended with aged (stabilized) composts contribute to lower carbon export.

Nutrients: Nutrients are susceptible to leaching from organic amended soils as the soil OM dissimilates. The extent of leaching is typically dependent on the application rate of compost and the source material. This was noticed between treatments in both studies. Discussed below are specific observations made between the treatment concentrations (mg/L) and mass transport (mg/ft^3) of TP and TN from TS1 and TS2.

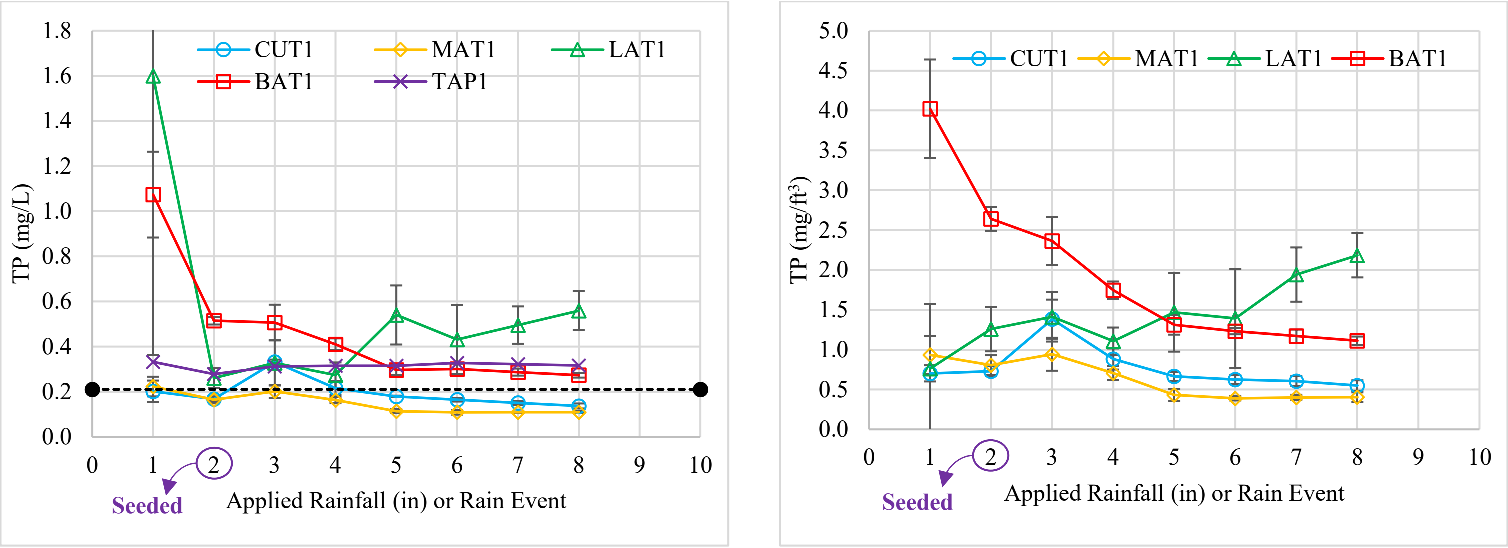
(a) Phosphorus Losses: Fig. 10 shows the four-replicate average concentrations and mass transport of TP for soils from TS1 and TS2. The concentration profile suggested that the TP release was higher in LAT1 and BAT1 treatments when compared to CUT1 and MAT1. LAT1 replicates performed differently within the group, with one replicate leaching 0.472 mg-P/L while another leached 3.37 mg-P/L during the first rain event. Similarly, TSS concentrations for LAT1 ranged from a low of 497 to 5550 mg-TSS/L for the same storm. As time progressed, the TP concentrations decreased and plateaued across CUT1, MAT1 and BAT1 treatments; however, LAT1s followed a different trend with a decrease in TP until rain event 4 and a slow increase after that. A potential saturation of LAT1 with weekly rain applications using tap water (influent) that contains ~ 0.3 mg-P/L could explain this increase in leachate TP. At this stage, the influent P can no longer be tied to the soil, as the soil matrix could have possibly been depleted of P adsorption sites. On the other hand, CUT1 and MAT1 treatments were shown to reduce the tap water TP levels throughout the study period. Since these soils are also deficient in P, the vegetative establishment was substandard (Section 4.7). Although BAT1 TP concentrations started at 1.07 mg-P/L (owing to its high levels of soil P (111 mg-P/kg)), the levels eventually decreased and achieved a steady release of TP as storms progressed. Of all the treatments, BAT1 soil conditions were slightly more acidic in nature and also contained higher Fe content, indicating that phosphate could be stabilized by binding to the surfaces of iron (and/or aluminum) oxide minerals under these conditions and thereby reducing the P release into the effluent (Spohn 2020).

The mass transport plot (Fig. 10b) shows that although the average leachate concentration of TP from LAT1 was the highest at the initiation of the first rain event, its corresponding mass transport followed the order of BAT1 > MAT1 > LAT1 > CUT1. This is explained by the large volume differences between LAT1 and other treatments. Since LAT1s retained more water, an average of 6% of the applied rain was leached, whereas the others ranged between 55 – 65% during storm 1. However, this was a one-time occurrence because volume differences among the treatments were less significant from storm 2 through 8, that is under wetted soil conditions as previously discussed. Cumulatively, greater mass of TP was lost through leachate from BAT1 treatment (Table 11).

Since TS2 soils contained the same base soil (CUT2), specific treatment impacts on the water quality can be discussed. With an exception to BAT2 treatments, CUT2, MAT2 and LAT2 leached around the same TP concentrations at the onset of rain event 1 (Fig. 10c). The temporal pattern of BAT2 TP quickly reduced and plateaued (as also observed in BAT1) at concentrations as low as 0.1 mg-P/L. CUT2 and LAT2 treatments started with high adsorption of P in their soil matrix but the leachate concentrations of TP escalated in subsequent rain events. Again, as available P in soil exceeded the plant-uptake demand and a dearth of adsorption sites, due to the contribution of additional P additions from weekly tap water applications, an increase in leachate P (as observed in CUT2 and LAT2) might be expected. Influent TP concentrations were higher across all the rain events and treatments, with an exception to rainfall event 8, where average TP concentrations in the LAT2 and CUT2 effluents were higher.

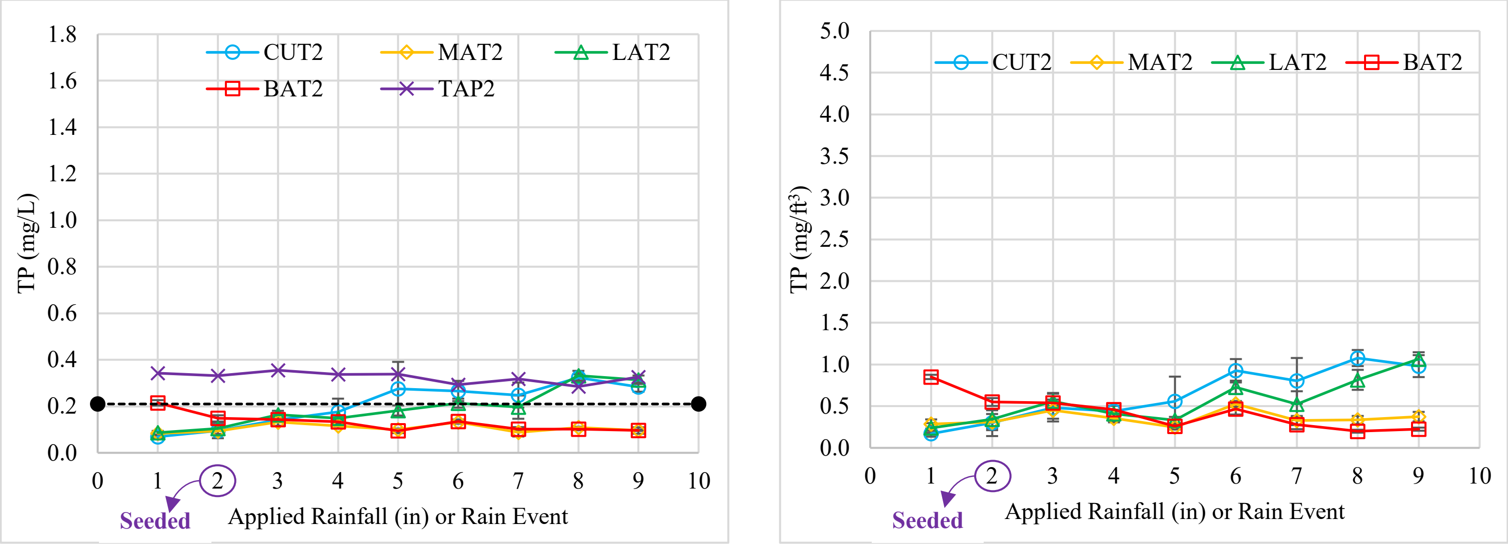
Unlike differences among TS1 TP concentrations vs mass transport trends, the TS2 mass transport plots aligned with that of the concentration plots (an upward trend in CUT2 and LAT2, a downward trend in MAT2 and BAT2; Fig. 10d). This was because the leachate volume were consistent within replicates and among treatment groups. More TP by mass was lost in the CUT2 treatments with lowest loss occurring in MAT2 (Table 11). Also, the TP mass transport was higher in TS1 when compared to the soil counterparts in TS2 by 1.07, 1.56, 2.3, 4.08 times for CUT, MAT, LAT and BAT treatments respectively.

(b) Nitrogen losses: Fig. 11 shows the four-replicate average concentrations and mass transport of TN for soils from TS1 and TS2. TN concentrations in the TS1 leachate samples exceeded the incoming tap water TN levels across all the treatments (Fig. 11a). BAT1 contributed to the highest release with a peak average of 191 mg-N/L during rain event 3. A decrease in BAT1 TN concentrations was seen soon after rain event 4 and became asymptotic at 36.6 mg-N/L after 8 in of total rainfall. MAT1 and LAT1 treatments followed the same trend as BAT1, since the concentrations declined and reached a steady state as the turf grass started to grow. CUT1 had a steady release of N throughout the rain events. CUT1 soil C:N ratio was high (25:1), which could have made N a limiting nutrient for plant growth (Section 4.7); it also showed up in the leachate at lower concentrations. Unlike TP, TN release in LAT1 showed a better consistency within its replicates. This is related to poor interactions between the anionic nitrogen species with the soil matrix which makes N more mobile and susceptible to leaching compared to P, particularly in the initial stages of the growth when the vegetation was not fully established. Previous research also noted a negative correlation of soil C:N with TN loss (Zhou 2017; Dise et al. 1998). This is similar to the results from this study, where the treatment with the lowest C:N ratio (BAT1), given its high N content, released greater amounts of TN via leachate. Similar to the TP mass transport, a dip was noticed in the TN plot (Fig. 11b, Rain Event 1) for LAT1 owing to the leachate volume variability. BAT1 exported significantly more TN by mass (by orders of magnitude), compared to the other treatments.



(a) Average TP Concentrations (TS1)

(b) Average TP Mass Transport (TS1)



(c) Average TP Concentrations (TS2)

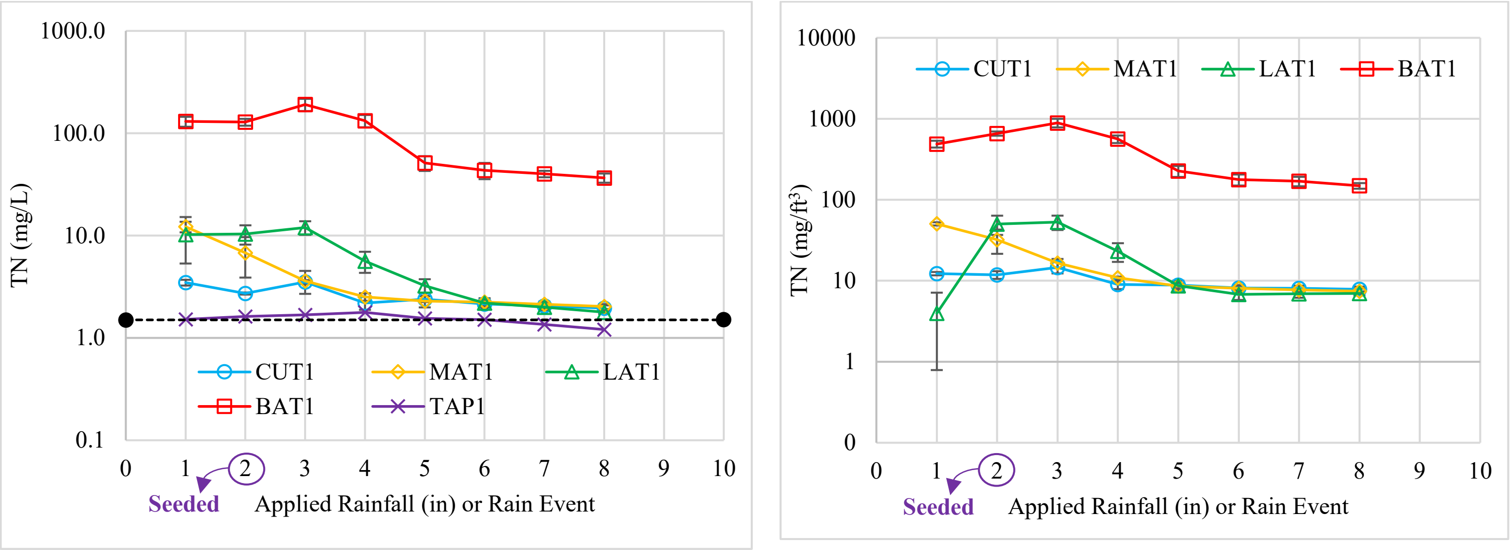
(d) Average TP Mass Transport (TS2)

Fig. 10. *Mean concentrations (**a** and **c**) and mass transport (**b** and **d**) of TP from treatments used in Tub Study 1 (TS1) and Tub Study 2 (TS2). Dashed line indicates typical urban stormwater mean concentration of TP = 0.21 mg-P/L (Pamuru et al. 2022)*

Table 11. *Cumulative Mass Transport (mg/ft^3) of leachate TP and TN from Tub Study 1 (TS1) and Tub Study 2 (TS2) treatments*

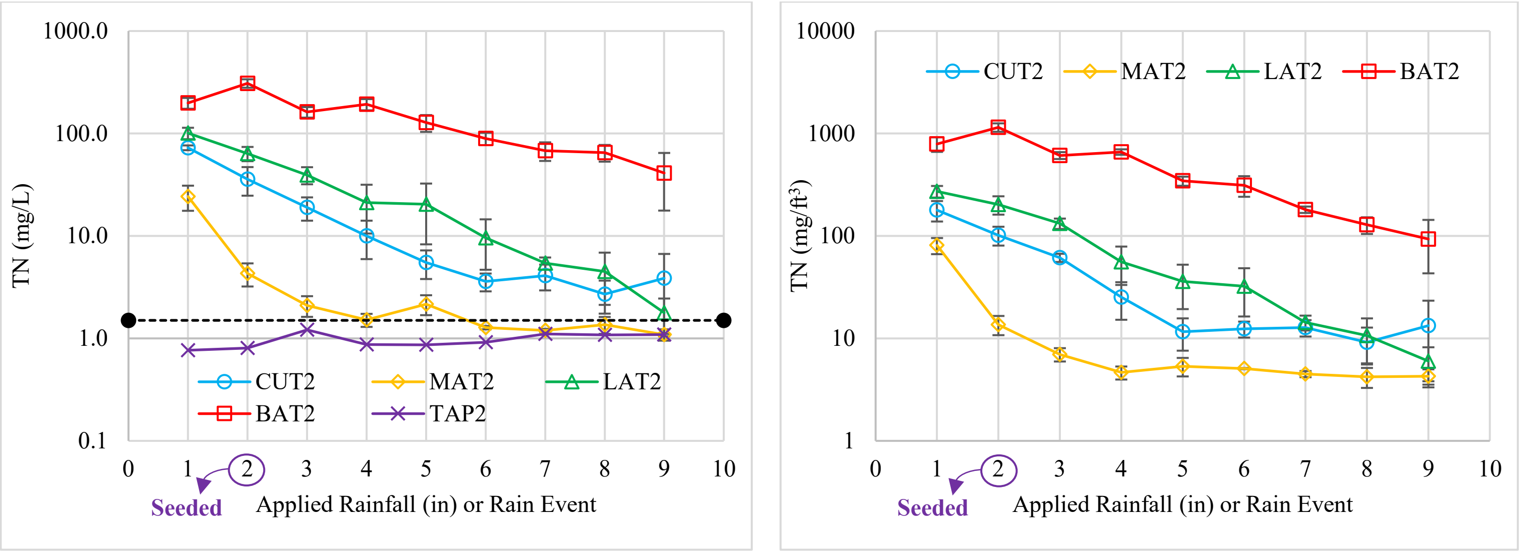
		CUT	**MAT**	**LAT**	**BAT**	**P-Value**
Total Phosphorus	TS1	6.14 ± 0.46a	5.01 ± 0.71a	11.5 ± 1.73b	15.6 ± 1.28b	< 0.0001
	TS2	5.74 ± 0.71b	3.21 ± 0.36a	5.01 ± 0.59b	3.82 ± 0.16a	< 0.0001
Total Nitrogen	TS1	80.6 ± 4.96a	141.8 ± 13.1b	159.7 ± 13.3b	3322 ± 86.4c	< 0.0001
	TS2	440.9 ± 64.8b	129.6 ± 13.9a	762.4 ± 66.1c	4262 ± 166.5d	< 0.0001

Notes: All results are expressed as mean ± SD. Values in each row which have different letters are significantly different (α = 0.05).



(a) Average TN Concentrations (TS1)

(b) Average TN Mass Transport (TS1)



(c) Average TN Concentrations (TS2)

(d) Average TN Mass Transport (TS2)

Fig. 11. *Mean concentrations (**a** and **c**) and mass transport (**b** and **d**) of TN from treatments used in Tub Study 1 (TS1) and Tub Study 2 (TS2). Dashed line indicates typical urban stormwater concentration of TN = 1.47 mg-N/L (Pamuru et al. 2022)*

TN measurements in the leachate varied among TS2 amended soils. Similar to TS1, average concentrations of TN were highest in the leachate from BAT2 (peak average concentration = 309 mg-N/L, storm 2) treatments, followed by LAT2 (peak average concentration = 101 mg-N/L, storm 1). CUT2 soil inherently leached high levels of TN (72.6 mg-N/L, storm 1) compared to the CUT1 (3.47 mg-N/L, storm 1) in TS1. Addition of leaf compost and biosolids to CUT2 contributed to higher TN leaching (see Fig. 11c). On the contrary, mulch OM reduced N leaching. However, the soil analysis showed TN content in MAT2 as greater than the control soil. We suspect this N drawdown was due to soil microorganisms assimilating soil-N while feeding on cellulose from the mulch, thereby tying up the nutrient. From the vantage of water quality, mulch amendments reduce the risk of polluting surface waters, however soil N can be limited in the context of that which is available for plant uptake (Section 4.7). There is a steady decline in TN concentrations across CUT2, LAT2, BAT2 treatments with each sequential rain event, yet soil C:N ratio is maintained. Cumulative TN mass transport from BAT2 (4262 mg/ft^3) was statistically higher compared to others, and MAT2 (129.6 mg/ft^3) loss was the lowest (Table 11). The temporal trends between TN average concentrations and mass transport of same treatment groups were similar because the TS2 leachate volumes did not significantly alter as mentioned earlier.

Table 12. *Concentrations and Mass Transport of TP and TN in leachate and runoff samples of Leaf compost Amended Topsoil (LAT1) from Tub Study 1 (TS1)*

LAT1 Concentrations (mg/L)									
Water Sample	**Rep**	***Total Phosphorus***				***Total Nitrogen***			
		Storm 2	*Storm 5*	*Storm 6*	*Storm 8*	*Storm 2*	*Storm 5*	*Storm 6*	*Storm 8*
Leachate	1	0.28	0.48	**NR**	**NR**	9.38	2.87	**NR**	**NR**
	2	**NR**	0.45	0.54	0.66	**NR**	2.86	2.52	1.82
	3	**NR**	0.73	**NR**	0.48	**NR**	3.28	**NR**	1.85
	4	**NR**	0.50	0.21	0.60	**NR**	3.94	2.26	1.73
Runoff	1	0.40	0.87	**NA**	**NA**	2.58	2.33	**NA**	**NA**
	2	**NA**	1.69	1.91	1.23	**NA**	3.76	3.30	2.51
	3	**NA**	2.00	**NA**	0.73	**NA**	4.33	**NA**	2.06
	4	**NA**	2.01	0.56	0.60	**NA**	6.0	2.39	1.83
LAT1 Mass Transport (mg/ft^3)									
Water Sample	**Rep**	***Total Phosphorus***				***Total Nitrogen***			
		Storm 2	*Storm 5*	*Storm 6*	*Storm 8*	*Storm 2*	*Storm 5*	*Storm 6*	*Storm 8*
Leachate	1	1.23	1.19	**NR**	**NR**	41.4	7.05	**NR**	**NR**
	2	**NR**	1.25	1.52	2.55	**NR**	8	7.04	6.99
	3	**NR**	2.21	**NR**	1.91	**NR**	9.87	**NR**	7.35
	4	**NR**	1.23	0.49	2.22	**NR**	9.75	5.36	6.42
Runoff	1	0.57	0.36	**NA**	**NA**	3.63	0.96	**NA**	**NA**
	2	**NA**	0.32	0.30	0.19	**NA**	0.72	0.51	0.39
	3	**NA**	0.25	**NA**	0.23	**NA**	0.54	**NA**	0.64
	4	**NA**	0.33	0.31	0.27	**NA**	0.98	1.35	0.83

NR: *not reported* in this table for brevity
NA: *not applicable* because no runoff was discharged from the corresponding LAT1 replicate

Using the information pertaining to the TN and TP stormwater EMCs available in the national stormwater quality and the BMP databases (https://bmpdatabase.org/), the median value of the TN is estimated to be 1.47 mg-N/L (N = 2186) and TP to be 0.21 mg-P/L (N = 7961) from across US urban land uses (Pamuru et al. 2022). The leachate effluent concentrations from TS1 and TS2 treatments exceeded the typical stormwater TN throughout the trial, except for MAT2, which had steady state values lower than 1.47 mg-N/L. CUT1, MAT1, MAT2 and BAT2 (50% of the treatments) released TP at concentrations lower than typical stormwater EMC (0.21 mg-P/L) by the end of the respective growth study.

(c) Surface water discharge (TS1): As mentioned previously, occasionally, LAT1 treatments produced surface runoff in addition to leachate. The soil type (silt loam) and its moisture conditions could have contributed to this irregularity of runoff occurrences. Table 12 shows TP and TN concentrations and the corresponding mass transport from when the LAT1 treatments discharged both leachate and runoff. Although a full suite of leachate data is available, Table 12 includes only the leachate data that corresponds to the observed runoff data to explain the difference in concentrations (and mass transports) in the two distinct discharges. TP concentrations in surface runoff were higher compared to subsurface (leachate) release across

all treatments. This is because the P in soils is relatively stable and immobile as it binds with minerals (Lehmann and Schroth 2002). On the contrary, TP mass transport indicated that more P by mass was lost to subsurface water than runoff because of the differences in volume between the two. Leachates had 3.4 to 18.8 times more volume than runoff. TN release in the leachate was more compared to runoff (as expected under pre-growth conditions); however, in time, the N release between the two aqueous pathways ranged between 1.73 – 6 mg-N/L (rain events 5, 6 and 8). Similar to P, more N was lost via leachate than runoff.

(d) Nutrient Speciation: A complete speciation of N and P was determined for the leachate samples collected from the TS1 and TS2 treatments (Fig. 12 and Fig. 13). The BAT1 soil from TS1 leached a notable fraction of NH_4-N in the first 4 rain events. Overall, NH_4-N in BAT1 effluent dropped from an average concentration of 93 mg-N/L to 1.1 mg-N/L from the initial to final rain event. Organic N (TON) was another major N species readily leachable in all TS1 treatments. Effluent TON fraction was particularly high until rain event 3. With time, as TON started to mineralize due to microbial activity and as subsequent nitrification occurred, the fraction of TON decreased and plant available NO_3-N became the dominant species (Fig. 12).

At the end of TS1 (rain event 8) and across all the treatments, NO_3-N in leachates was below 2.0 mg-N/L in all soils except for BAT1 which was still leaching N (24 mg-N/L). Effluent from TS2 treatments contained higher N concentrations, compared to their treatment counterparts in TS1. TON and NO_3-N continued to be the major species in the leachate samples. A small amount of NH_4-N was found after the first rain event in BAT2 alone, unlike BAT1 where the NH_4-N release continued until the 4th rain event. The same biosolid material (originally procured in May 2021) used in the BAT1 blend was stored in closed-lid buckets and reused in September 2021 to prepare BAT2. No additional analysis for N speciation in biosolids was preformed before TS2. However, no apparent trend was noticed in the fractional changes of N species (NO_3-N and TON) among soils for each rain event.

Unlike in TS1, comparatively more TON (albeit fractionally small compared to NO_3-N) remained in the leachates over the TS2 study period for all soils. A trending decline in TN leached is noted for all TS2 soils with BAT showing the most dramatic declines, yet having substantially higher concentrations than the other soils. This was also noted in TS1. NO_3-N remains the dominant N leached from all the soils, with incrementally less TON found through successive rain events. A transient product of nitrification, nitrite (NO_2-N) was analysed for a few rain events from TS1 and TS2 (not shown in Fig. 12). Our findings show that NO_2-N was negligible (all less than 2% of TN) in the mass balance of N species for all soils in both TS1 and TS2. Tap water N was almost entirely (91.5 to 100%) in the form of NO_3-N.

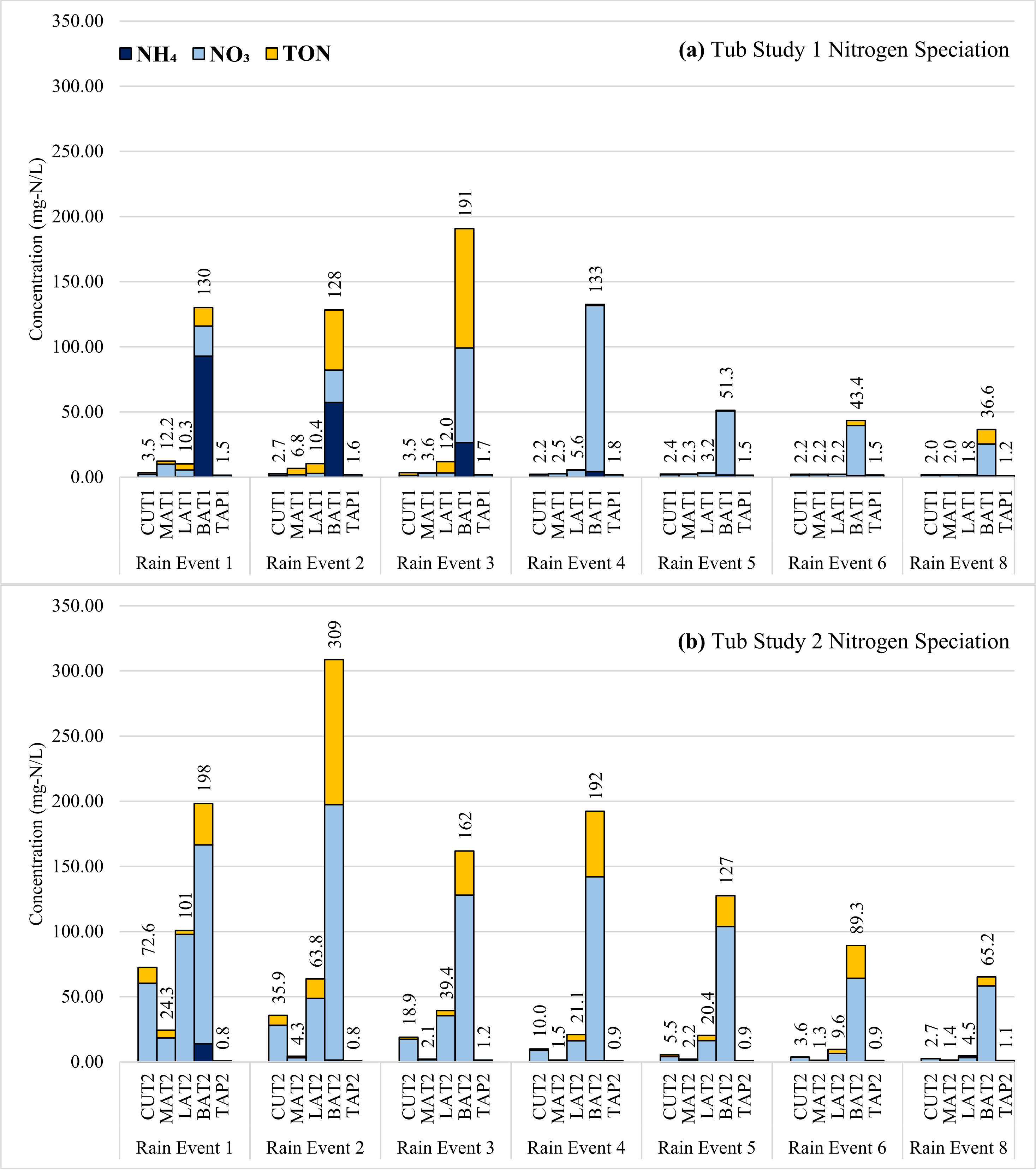


Fig. 12. *Average concentrations of nitrogen species Tub Study 1* ***(a)*** *and Tub Study 2* ***(b)*** *treatments. Values on top of the bar plots denote the respective TN concentrations*

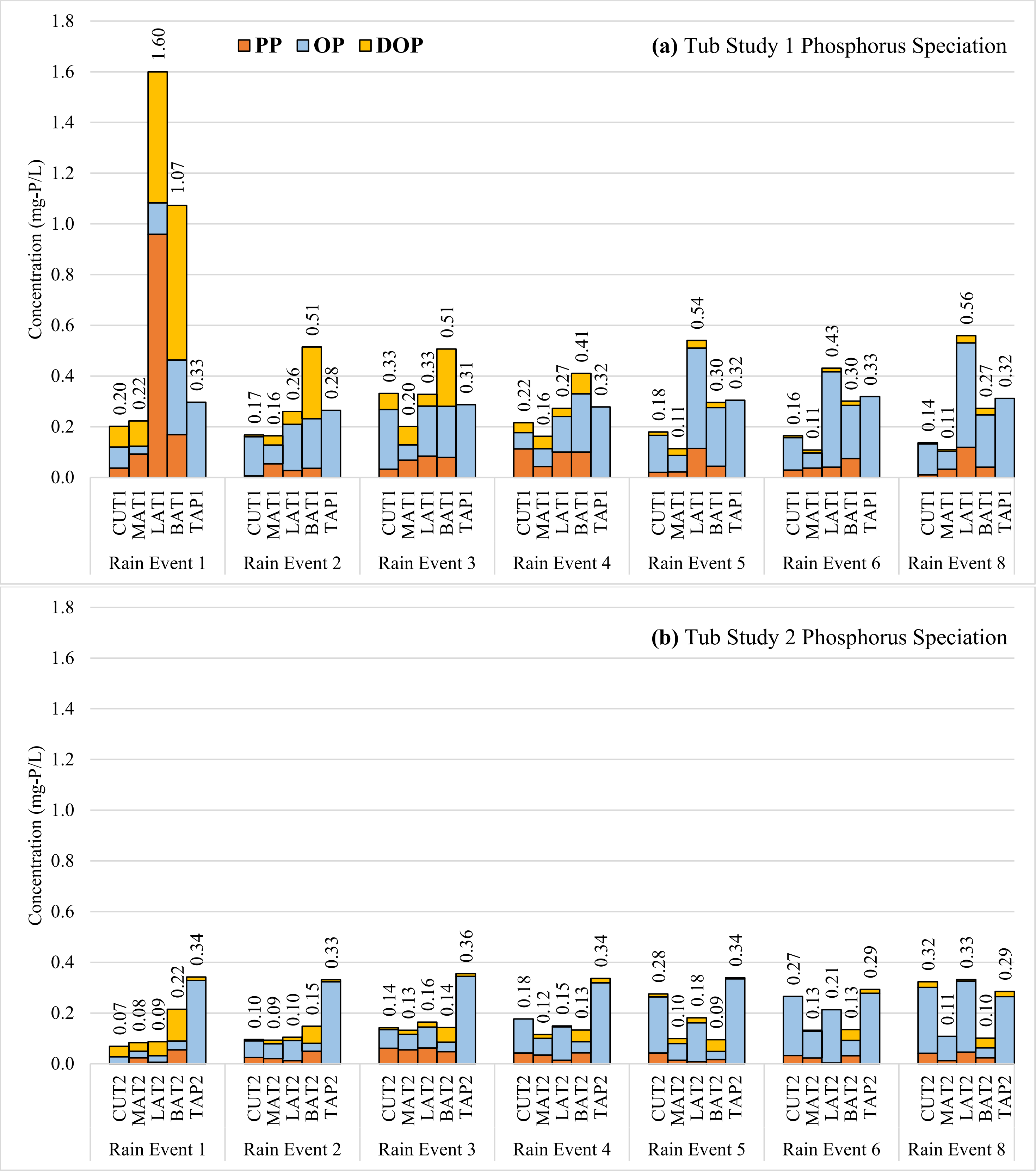


Fig. 13. *Average concentrations of phosphorus species Tub Study 1* ***(a)*** *and Tub Study 2* ***(b)*** *treatments. Values on top of the bar plots denote the respective TP concentrations*

Unlike the N speciation, major ionic P species appeared in both dissolved readily available P (OP), organic phosphorus that is dissolved in water (DOP) and particulate forms (PP) (Fig. 13). Across TS1 treatments, the highest average DOP concentration was recorded in the BAT1 treatment (0.61 mg-P/L) and highest average PP was recorded in the LAT1 treatment (0.96 mg-P/L) after 1 in rainfall. After the first flush of sediment in the LAT1 treatments in rain event 1, the fraction of PP was significantly reduced and leached in the range of 0.03 to 0.12 mg-P/L in the later rain events. Percent PP of TP followed no specific trend across the treatments. However, there was a decline in %DOP from 41 to 3%, 45 to 6%, 32 to 5% and 57% to 10% for CUT1, MAT1, LAT1 and BAT1 treatments. An opposite trend was observed in OP where the percent fraction went from 41 to 89%, 14 to 64%, 8 to 74%, 27 to 75% from CUT1, MAT1, LAT1 and BAT1. Because there had been a continuous input of OP from tap water during each rain event, it is difficult to discern if reduction in the DOP fraction over time is associated with its minerlization and/or decomposition to OP, due to the inability of the soil to adsorb any further OP, or both.

TS2 soil treatments dictated that a considerable fraction of PP contributed to the total leachable P in the water samples. Percent PP was as high as 42.7%, 41.5%, 37.8% and 33.4% of TP for CUT2, MAT2, LAT2 and BAT2 respectively across the study. The temporal trends of DOP and OP species in TS2 corroboarated with that of TS1. The majority of the DOP leached during the initial rain events; as the vegetation cover grew, OP became the dominant form in the leachate. Although BAT2 DOP fraction was reduced with each rainfall application, the final average concentration still amounted to 0.038 mg-P/L (37.5% of TP). Consistent observations between TS1 and TS2 suggest that DOP has the potential to be leached along with OP in organic soils, and treatments should be designed to curb these losses (McDowell et al. 2021).

4.7. Tub Study Vegetation Establishment

4.7.1. Percent Grass Coverage

Weeds were allowed to grow in TS1 but not in TS2. They were removed at the conclusion of TS1 to determine final turfgrass percent coverage. Excluding MAT2 microcosms, the final % coverage was better in TS2 (a fall experiment) than in TS1 (a summer experiment). The overall difference is attributed to the milder fall temperatures preferred by the cool season grass (SHA) mix used in both studies.

TS1: Final turfgrass coverage was significantly higher in all microcosms that received a soil amendment as compared to the non-amended control (CUT). Coverage was significantly higher in the BAT1 treatment than all other CATs. Weekly average coverage, (including weeds) are summarized in Fig. 14. Coverage must exceed 95% to qualify for final acceptance according to SHA *Standard Specifications for Construction and Materials* (705.03.10 - Final Acceptance). Mean final coverage did not exceed 95% for any treatment at any time during TS1. In summary, the evaluation of TS1 % coverage indicates that attempts to establish turfgrass during the summer are susceptible to failure regardless of which treatment is used.

TS2: Weekly coverage results for TS2 are summarized in Fig. 15. Mean turfgrass coverage was ≥ 90% for the CUT2 treatment and ≥ 95% for LAT2 and BAT2 treatments. Mean coverage for MAT2 was 32.8%, which was significantly lower than all other treatments. When TS2 concluded, coverage was trending up for the CUT2 microcosms but had plateaued for the remaining microcosms. The overall evaluation of TS1 and TS2 percent coverage indicates that mulch should not be used alone as a source for raising the concentration of OM.

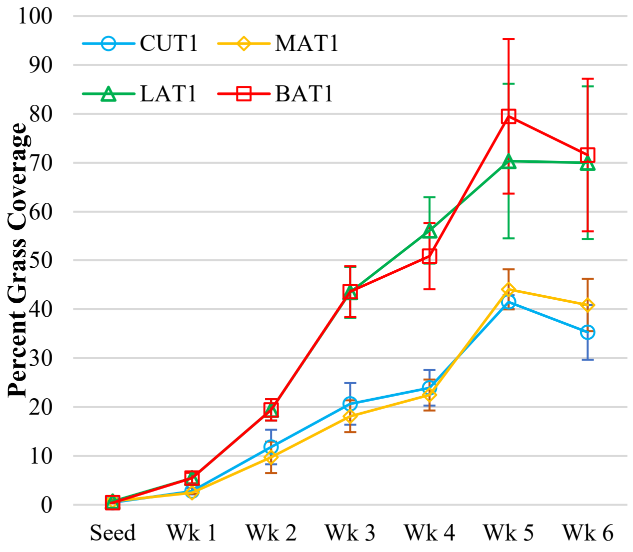


Fig. 14. *Weekly % Coverage from Tub Study 1*

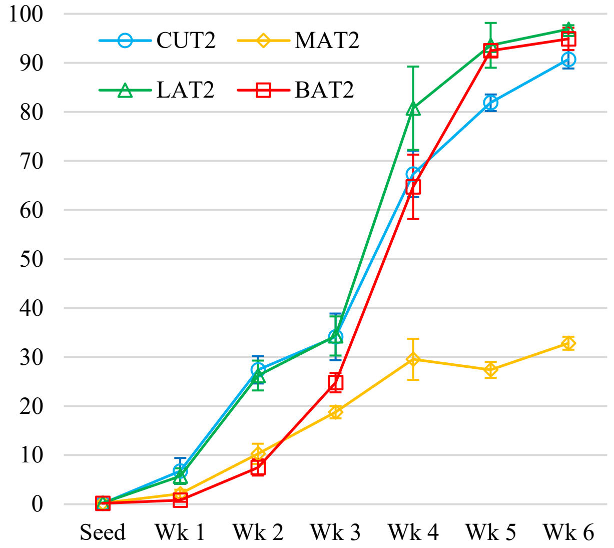


Fig. 15. *Weekly % Coverage from Tub Study 2*

4.7.2. Growth Measurements

All growth measurements are summarized in Table 13. Mean turfgrass heights for all TS1 treatments exceeded the minimum (10.16 cm; 4 in) required for SHA final approval. All TS2 mean heights also exceeded the specification, although the mean height for MAT2 (10.8 cm) was close the minimum requirement and was statistically lower than all other treatments. The mean heights for the remaining TS2 treatments were > 20.7 cm.

Table 13. *Vegetation growth measurements for Tub Study 1 (TS1) and Tub Study 2 (TS2). The treatments include a control (CUT), a mulch amended soil (MAT), a leaf compost amended soil (LAT), and a biosolids amended soil (BAT).*

		CUT	**MAT**	**LAT**	**BAT**	**P-Value**
Final % Cover	TS1*	38.8 ± 4.8a	50.3 ± 7.1b	41.3 ± 9.5b	70.8 ± 12.5c	0.001
	TS2	90.7 ± 1.8b	32.8 ± 1.3a	96.9 ± 0.8c	94.9 ± 2.3bc	< 0.001
Height (cm)	TS1	11.1 ± 0.5a	12.5 ± 1.2ab	16.55 ± 1.9b	20.8 ± 0.5c	< 0.001
	TS2	20.7 ± 0.8b	10.8 ± 1.4a	26.6 ± 3.8bc	31.6 ± 1.9c	< 0.001
Shoot Dry Mass (g)	TS1	5.6 ± 1.5a	8.15 ± 2.2a	18.0 ± 2.7b	24.15 ± 3.2b	< 0.001
	TS2	24 ± 3.7b	7.47 ± 2.0a	39.4 ± 3.2c	67.7 ± 7.3d	< 0.001
Root Dry Mass (g)	TS1*	0.47 ± 0.16	0.41 ± 0.17	0.53 ± 0.05	0.40 ± 0.05	0.396
	TS2	0.94 ± 0.06b	0.33 ± 0.13a	0.85 ± 0.25ab	0.58 ± 0.18ab	< 0.001
Root-Shoot Ratio	TS1	3.41 ± 1.94ab	1.77 ± 0.52b	1.09 ± 0.27ab	0.60 ± 0.15a	0.01
	TS2	1.75 ± 0.66b	1.55 ± 0.36b	0.79 ± 0.28ab	0.30 ± 0.07a	<0.001

Notes: All results are expressed as mean ± SD. Values in each column which have different letters are significantly different (a = 0.05).

*Includes weeds

TS1 mean shoot dry mass (SDM) included weeds and was significantly higher for LAT1 and BAT1 as compared to CUT1 and MAT1. TS2 mean SDM was significantly different across all treatments (MAT2 < CUT2 < LAT2 < BAT2). Mean root dry mass (RDM) was not statistically different between treatments in TS1. In TS2, a CUT2 replicate was removed when determining the mean RDM because it was nearly 2 times greater than the other values recorded for that treatment. However, the replicate was not removed when evaluating root-shoot ratios (R:S). MAT2 root dry mass was statistically lower than CUT2 ($F(3,11) = 9.26$, $p = 0.002$), which had the highest mean.

Mean R:S was lowest in BAT for both tub studies. In TS1, BAT1 was statistically lower than MAT1 and in TS2, BAT 2 was statistically lower than CUT2 and MAT2. Despite BAT1 and BAT2 having the highest mean averages for TS1 % cover, TS1 and TS2 shoot dry mass, and TS1 and TS2 height, BAT1 had the lowest mean root dry mass in TS1 and BAT2 root dry mass was lower than CUT2 and LAT2 in TS2. Limited root growth can be explained by the high availability of plant available N (PAN) at the beginning of the experiment. Turfgrasses respond to high nitrate levels by assigning carbohydrates from photosynthesis to amino acid production instead of to storage in the form of sugars in roots. This occurrence results in top growth at the expense of root growth, especially during the summer months for cool season grasses (Carrow et al. 2001a). Root growth is important for stabilizing soil after construction activities to prevent erosion. Additionally, a well-established root system protects against drought and other environmental stresses. In summary, the application of biosolids above yearly N requirements in amended topsoil should be avoided along road shoulders to ensure healthy root development.

4.7.3. Plant Tissue Analysis

The following nutrient deficiencies were identified by tissue analysis and are summarized in Table 14.

CUT1: N
MAT1: N, P
LAT1: N, P
BAT1: P, Fe

CUT2: N, P, S, Cu, Zn, B
MAT2: N, P, S, Cu
LAT2: N, P, Cu, B
BAT2: P, B

CUT treatments: Tissue analysis revealed a N deficiency in both CUT treatments. CUT1 turfgrass underperformed as compared to the other TS1 treatments, which was likely due to low N availability tied to a high soil C:N ratio. The median C:N ratio is 12:1 for the Ap horizon (Weil and Brady 2017). The CUT1 ratio was 25:1. When there is not enough N available in the soil to satisfy both soil microbes and plant communities, plant growth is reduced and the decay of organic materials can be delayed. Although nitrate and ammonium concentrations for TS1 are not known, TS1 root growth supports the theory that plant available N was limited. Carrow et al. (2001) reports that the turfgrass root growth rate is highest at low to medium N sufficiency levels and drops dramatically above a medium sufficiency level. CUT1 mean RDM was the second highest despite having the lowest SDM. Additionally, the mean root:shoot ratio for CUT1 was 3.41 ± 1.94 g as compared to 1.77 ± 0.52, 1.09 ± 0.27 and 0.6 ± 0.15 for MAT1, LAT1, and BAT1, respectively. A N deficiency was also noted in CUT2 leaf tissue as well as similar trends in root growth. However, the C:N ratio was lower in TS2 (11:1) and growth measurements were better across all treatments. Analysis of TS2 plant tissue revealed several nutrient deficiencies in CUT2 turfgrass (see above). A P deficiency was the only deficiency identified by both the CUT2 soil analysis and tissue analysis. The before and after soil analyses highlighted a sharp drop in S, which showed up as a deficiency in the CUT2 tissue analysis. S deficiencies are associated with soils that are: heavily leached, sandy, and do not receive atmospheric sulfur (Carrow et al. 2001b). CUT2 treatments meet all criteria. The micronutrient deficiencies (Cu, Zn, and B) are associated with alkaline soils (pH > 7), such as CUT2 (Carrow et al. 2001a). Despite these deficiencies, CUT2 establishment rates were better than CUT1 rates, which are attributed to cooler temperatures and a lower C:N ratio.

MAT treatments: MAT1 weekly percent coverage, height and SDM was comparable to LAT1. Like LAT1, the C:N ratio (19:1) was higher than the mean for cultivated surface horizons. Though PAN was not tested, TN was higher in MAT1 soil at the beginning of the experiment. Additionally, a lower R:S ratio indicates that available N could have been higher in MAT1 than CUT1. MAT1 had a P deficiency as determined by the soil analysis and tissue analysis. Therefore, the limiting factor for MAT1 was most likely P, not N. The incorporation of mulch to the base soil in MAT2 drove the C:N ratio up from 11:1 in the base soil to 20:1. MAT2 soil was also deficient in P at the beginning and end of TS2. Low N and P availability are likely responsible for poor turfgrass established as determined by growth measurements in MAT2 microcosms. N and P deficiencies were confirmed by the tissue analysis as well as S and Cu deficiencies, which were present in the base soil. The addition of mulch did not alleviate the S and Cu deficiencies in the base soil.

LAT treatments: LAT1 soil was initially deficient in P but extractable P increased over the course of the study. Even so, the tissue analysis revealed a P deficiency as well as a N deficiency. Soil N was higher than CUT1 and MAT1 treatments but lower than the BAT1 treatment. When including weed growth (attributed to the source of the soil and not the treatment), LAT1 growth measurements followed a similar pattern. Since the base soil for each TS1 differed, it is difficult to attribute the improved soil and growth measurements of LAT1 to the use of leaf compost. However, TS2 used the same base soil across treatments and suggests that the incorporation of leaf compost improved soil P and N and thereby turf establishment while maintaining a 12:1 C:N ratio.

BAT treatments: BAT1 and BAT2 had the lowest C:N ratios, lowest pH values, highest SS concentrations (above SHA specifications) and were the only treatments that did not result in leaf tissue N deficiencies. High N uptake in the BAT treatments is attributed to high TN concentrations as well as low C:N ratios. BAT1 had the highest % coverage, height, and SDM in TS1, likely due to N availability. (In TS2, BAT2 and LAT2 % coverage and height were statistically similar while BAT2 SDM was greater.) The limiting factor for BAT1 and BAT2 growth was most likely P. As a result of the wastewater treatment process, biosolids P is largely tied to Fe, Al, and Ca as inorganic phosphates, which are not plant available (Badzmierowski and Evanylo 2018). BAT1 and BAT2 soil and tissue results are supported by this known occurrence. Regardless, growth was not inhibited by P availability or SS concentration as compared to the other treatments. Additionally, 4 of the 6 nutrient deficiencies observed by the analysis of CUT2 tissue were not seen in BAT2 tissue. Biosolids haven been shown to be a comprehensive alternative to synthetic fertilizers when soil has multiple deficiencies, especially micronutrient deficiencies, since all nutrients are present (Badzmierowski and Evanylo 2018; Richards et al. 2011).

Table 14. *Summary of turfgrass tissue analysis for Tub Study 1 (TS1) and Tub Study 2 (TS2)*

Nutrient	Sufficiency Range*	Study	Control	Mulch	Leaf	Biosolids	P Value***
N (%)	4.50 - 6.00	TS1	**1.8 ± 0.1ab**	**2.0 ± 0.1b**	**1.6 ± 0.1a**	4.7 ± 0.1c	< 0.001
		TS2	**1.47 ± 0.12a**	**1.29 ± 0.07a**	**1.92 ± 0.36a**	4.51 ± 0.23b	< 0.001
P (%)	0.30 - 0.60	TS1	0.36 ± 0.04c	**0.23 ± 0.03b**	**0.15 ± 0.01a**	**0.26 ± 0.01bc**	< 0.001
		TS2	**0.12 ± 0.008a**	**0.15 ± 0.005b**	**0.15 ± 0.013ab**	**0.24 ± 0.030c**	< 0.001
K (%)	2.20 - 2.60	TS1	3.13 ± 0.04	4.00 ± 0.19	4.21 ± 0.14	5.07 ± 0.52	NA
		TS2	3.18 ± 0.20	2.79 ± 0.21	4.03 ± 0.44	4.51 ± 0.20	NA
Ca (%)	0.50 - 0.75	TS1	0.92 ± 0.05	1.15 ± 0.20	0.70 ± 0.02	1.06 ± 0.03	NA
		TS2	0.82 ± 0.05	1.00 ± 0.06	0.85 ± 0.17	1.09 ± 0.12	NA
Mg (%)	0.25 - 0.30	TS1	0.62 ± 0.05	0.53 ± 0.05	0.48 ± 0.02	0.42 ± 0.01	NA
		TS2	0.37 ± 0.02	0.39 ± 0.02	0.39 ± 0.02	0.48 ± 0.02	NA
S (%)	0.2 - 0.45 **	TS1	0.32 ± 0.03	0.32 ± 0.02	0.22 ± 0.01	0.27 ± 0.01	NA
		TS2	**0.16 ± 0.01ab**	**0.15 ± 0.01a**	0.20 ± 0.02b	0.28 ± 0.01c	< 0.001
Fe, ppm	100 - 300	TS1	134 ± 5bc	396 ± 249c	164 ± 49c	**93 ± 10a**	0.02
		TS2	280 ±126	389 ± 129	207 ± 41	241 ± 44	NA
Mn, ppm	50 -100	TS1	99 ± 6	146 ± 15	73 ± 13	290 ± 7	NA
		TS2	73 ± 4	106 ± 5	65 ± 6	71 ± 3	NA
Cu, ppm	8 - 30	TS1	9	11 ± 1	9 ± 1	12 ± 1	NA
		TS2	**6 ± 1a**	**6 ± 1a**	**7 ± 2a**	13 ± 1b	< 0.001
Zn, ppm	25 - 75	TS1	43 ± 7	34 ± 3	28 ± 1	72 ± 12	NA
		TS2	**20 ± 1a**	30 ± 3b	26 ± 5ab	41 ± 3c	< 0.001
B, ppm	6 - 30	TS1	11 ± 1	11 ± 1	17 ± 1	9	NA
		TS2	**5 ± 0.8ab**	6b	**4.75 ± 0.5a**	**4.25 ± 0.5a**	0.004

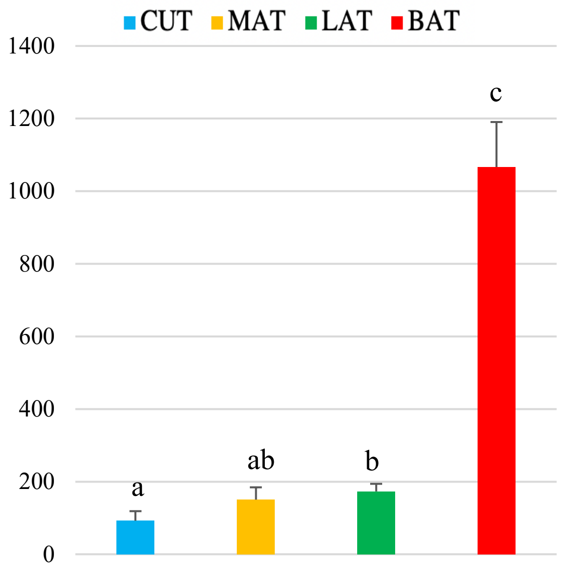
Notes: All results are expressed as mean ± SD. Deficiencies are denoted with boldface font. When deficiencies occurred, ANOVA was performed to determine significant differences between treatments. Values in each row which have different letters are significantly different (α = 0.05).

* For Creeping Bentgrass (Mills and Jones 1996)
** (Jones 1980)
*** Statistical differences were not investigated unless a nutrient deficiency was noted.

4.7.4. Nitrogen and Phosphorus Uptake

Plant uptake of N and P is summarized in Fig. 16 - Fig. 19. N and P uptake was overall greater for TS2 than TS1. This is best explained by the seasonal growth habits of the cool season grasses used in this study. Nitrogen uptake was significantly greater for BAT treatments than all other treatments across studies (TS1: F (3,12) = 196.5, p < 0.001; TS2: F(3,12) - 112.3, p < 0.001). All treatments except the BAT treatments resulted in leaf tissue N deficiencies. Soil N was highest in BAT treatments while the C:N ratios were low. The combination of these factors likely allowed for N mineralization as the experiment progressed thereby allowing for high levels of N uptake. In TS2, N uptake was significantly lower than all other treatments for

MAT2 (F (3,12) = 112.3, p < 0.001). Although the mulch amendment increased soil N, it also increased the C:N ratio which lowered PAN.



Note: Weed uptake is not included.

Fig. 16. *N Uptake (mg) from Tub Study 1*

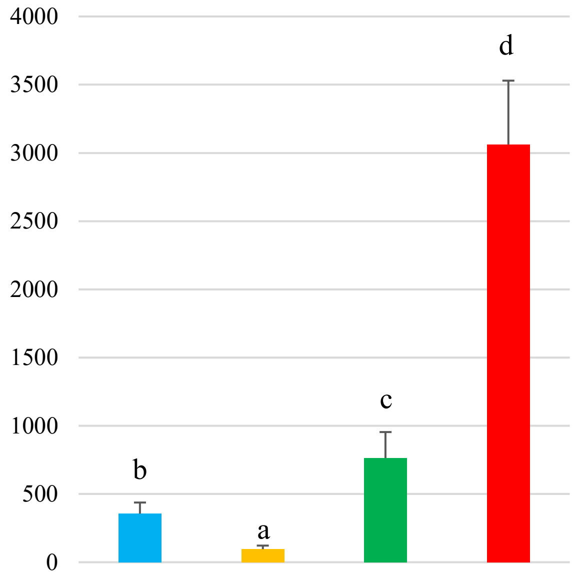
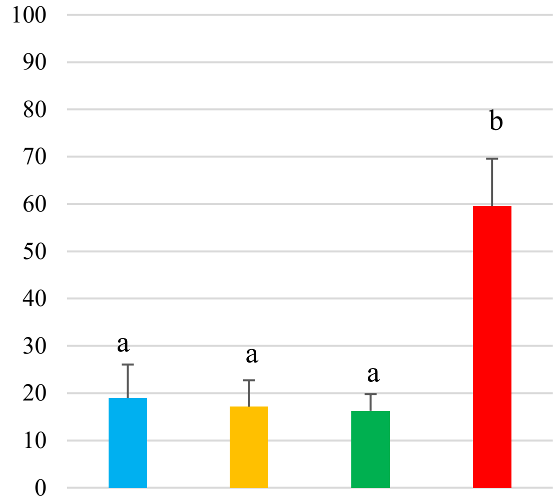


Fig. 17. *N Uptake (mg) from Tub Study 2*



Note: Weed uptake is not included.

Fig. 18. *P Uptake (mg) from Tub Study 1*

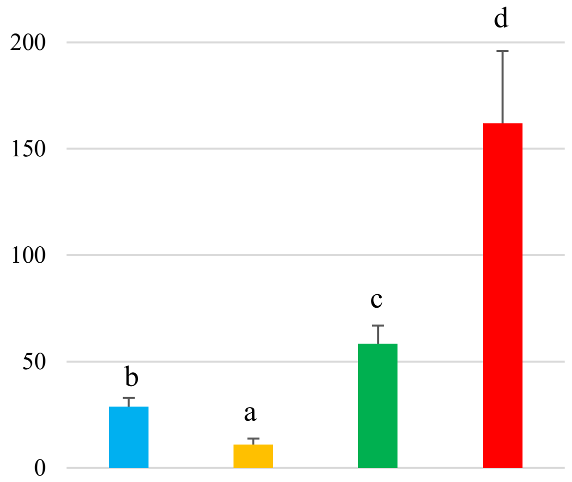


Fig. 19. *P Uptake (mg) from Tub Study 2*

Like N, P uptake was significantly greater for BAT treatments than all other treatments across studies (TS1: F(3,12) = 36.46, p < 0.001; TS2: F(3,12) - 57.9, p < 0.001). All treatments except the CUT1 resulted in leaf tissue P deficiencies. There is evidence from the leaching studies that the CUT1 and MAT1 and all TS2 soils retained tap water P since the concentrations of leachate P were less than the concentration in the tap water. This helps explain why there were widespread tissue P deficiencies.

5. CONCLUSIONS

Soil Producer Interviews: Thirteen SHA qualified topsoil producers were interviewed to understand the methods and major issues surrounding the use of compost in furnished topsoil. The major conclusions from these interviews are:

1. If producers incorporate organic amendments, composted yard waste is the preferred product; however, it is limited in supply due to seasonal availability and demand.
2. Finely shredded mulch, which is usually aged for some time, is another popular and cost-effective option that soil producers use to raise the OM content of furnished topsoil.
3. Biosolids were not used by any of the producers interviewed in 2020 as the primary amendment to raise the OM content of soil.
4. Cost, which includes the material cost as well as the cost of transportation, is the dominant factor that determines which amendments are used by soil producers to raise the OM content of topsoil.
5. Soil producers reported that organic amendments increase pH and soluble salts to levels that exceed SHA furnished topsoil standards. (Note: Addition of mulch, leaf compost and biosolids did not result in increases in pH in the tub studies described below.)
6. Inconsistencies in pH and OM among commercial testing labs made it difficult for soil producers to know whether soil would meet SHA specifications unless soil producers used Agrolab for testing. This is because at the time of the interviews (summer of 2020), SHA used AgroLab for quarterly soil tests.
7. Soil producers would like to see their SHA quarterly soil test results to better judge what is required to "correct" their products.

Column Studies: Ten topsoil samples voluntarily supplied by soil producers who participated in the research interviews were sequentially leached with 10.16 cm (4 in) of DI water over time to measure the concentration of ortho-P, TP, and TN in the leachate. The samples included unamended soil and soil amended with composted yard waste, mulch, mushroom compost, or a combination of mulch and biosolids. The column studies resulted in the following conclusions:

1. The findings corroborate research by others that soil P concentration does not alone determine the potential for P leachate loss. Furthermore, a single general indicator does not exist. The interplay of factors such as soil texture, soil pH, and CEC along with the amendment effects on these parameters influence P losses and are difficult to predict.
2. High soil TN plays a significant role in increasing N losses as well as a low C:N ratio of the amended soil.
3. Research shows that phosphorus is relatively stable in soil. However, leachate losses of P were higher when the organic P content of soil was high as demonstrated by samples B, D, and I as well as tub study LAT and BAT treatments.

Greenhouse Tub Studies: Two greenhouse microcosm studies (TS1; early summer, 2021 and TS2; Fall, 2021) were conducted in a controlled greenhouse environment, to identify the effects on vegetation establishment, water quality and the engineered properties of topsoil when it is incorporated with organic amendments. Each study consisted of four treatments (with four replicates of each) and included an unamended control soil (CUT), a mulch amended soil (MAT), a leaf compost amended soil (LAT), and a biosolids amended soil (BAT). TS1 MAT and LAT treatments were mixed by Maryland topsoil producers. TS1 BAT and all TS2 amended soils were mixed by the research team. The amendments used in TS2 raised the OM content of the control soil (CUT2) from 4.34% to 6.86%, 5.92%, and 5.64% for MAT2, LAT2, and BAT2, respectively. Before and after soil characteristics, growth measurements and leachate quality are summarized below by treatment.

CUT Treatments: Both CUT treatments met the SHA furnished topsoil specification for OM (4 - 8 %). Nevertheless, vegetation establishment for CUT1 was significantly less than LAT1 and BAT1, which had lower OM concentrations. In TS2, CUT2 was deficient in P and turf grown in CUT2 had N, P, S, Cu, Zn, and B deficiencies as identified by tissue analysis. CUT2 turf establishment was insufficient (90%) after six weeks, even though the OM content met specifications. Leachate losses indicate that TP release from CUT1 and CUT2 was comparable, as both soils were initially low in TP. Although the N content of CUT1 and CUT2 soils were similar, 5.5 times more cumulative N mass transport (CMT) was lost from CUT2 soil compared to CUT1 due to its low C:N ratio.

MAT Treatments: Vegetation establishment was insufficient for both MAT treatments as compared to SHA standards and were low compared to LAT1, BAT1 and all other TS2 treatments. The C:N ratio for both mulch treatments was near 20:1. TS2 demonstrated that wood mulch raised the C:N ratio of the control soil likely due to the high C:N ratio of the amendment. Leaf N deficiencies were identified in both treatments suggesting a N drawdown associated with the high C amendment. TP leachate losses from MAT treatments were lower than the typical stormwater concentrations from US highways (0.18 mg-P/L). Therefore, the mulch amendment in both studies effectively reduced soluble P. In TS2, addition of mulch to CUT2 lowered the N release in leachate, again attributed to the increase in the C:N ratio of the control soil. MAT1 and MAT2 CMTs for both TP and TN were comparable (TP: 5.01 mg/ft^3 for MAT1 and 3.21 mg/ft^3 for MAT2; TN: 141.8 for MAT1 mg/ft^3 and 129.6 for MAT2 mg/ft^3).

LAT Treatments: Although several producers suggested that the addition of compost amendments raises soil pH, the pH of LAT soils was comparable to CUT soils. The composted leaf mulch amendment did not alter the pH of the amended soil, as compared to the control in TS2. LAT1 vegetative growth was greater than CUT1 growth in TS1. In TS2, Leaf S and Zn deficiencies were not seen in LAT2 turf, but N, P, Cu, and B deficiencies were observed. Turf establishment in LAT2 surpassed CUT2. TS2 percent coverage and height were comparable to BAT2, though shoot dry mass was higher in BAT2. The concentration of TP in LAT1 soil was higher at the end of the experiment than it was at the beginning, indicating that LAT1 adsorbed P from tap water. On the contrary, in TS2, the soil concentration of TP was sufficient at the beginning of the experiment and deficient at the end. Leachate volume and suspended solids and TP concentrations in leachate showed significant variability among LAT1 replicates due to the higher fines content in the soil. Although LAT2 was also a silt loam soil, the standard deviation of the LAT2 replicates was smaller compared to the LAT1 soil. Increases in temporal TP concentrations in the leachate indicate saturation of P adsorption sites in both LAT1 and LAT2. In TS2, the leaf compost amendment increased the N content in the control soil (CUT2) and decreased the C:N ratio. This prompted higher N release in LAT2 leachate at the beginning of the study; however, the concentrations decreased after the vegetation was fully established. Of the eight treatments used in TS1 and TS2, LAT1 was the only soil that occasionally produced measurable runoff, which could be attributed to the texture of the base soil and not the treatment itself.

BAT Treatments: In TS2, biosolids (BAT2) lowered the average pH of the control soil from 7.2 to 6.8 and increased the EC of the control from 0.3 mmho/cm to 1.89 mmho/cm in the BAT2 soil. Among the TS1 treatments, the lowest soil pH and highest EC was found in BAT1. Although the soil EC for both BAT1 and BAT2 exceeded the SHA specification (>0.78 mmho/cm), this did not impede growth and these treatments met the requirements for final approval of vegetative establishment during their respective growth periods. In TS2, biosolids were a good source of micronutrients for soil as the plant micronutrient deficiencies seen in CUT2 tissue were not seen in BAT2 tissue. However, a P deficiency was noted in TS2 tissue despite the high P content of BAT2 soil. This is likely due to P complexation with soil minerals. Similarly, the steady state TP concentrations in the leachate were lower than the influent TP, suggesting P uptake capacity in the soils. Low C:N ratio and high N content in BAT soils contributed to high release of nitrogen species in the leachate; however, the high N enhanced grass coverage in both studies. Final average TN concentrations from BAT1 and BAT2 exceeded typical highway stormwater concentrations of TN. Evidence of Storm 1 NH_4-N leaching was also associated with BAT treatments because of high NH_4-N content in the amendment. The high N content provided by biosolids is likely responsible for the observed suppressed root growth in BAT treatments. Future studies should be conducted to determine if high biosolids in CATs for highway use have impacts on soil stabilization and the resiliency of turfgrass exposed to environmental stresses such as summer heat, climate change, drought etc. due to suppressed root growth.

Geotechnical Studies: The soils from the tub study experiments were tested for the following geotechnical properties: particle size distribution (PSD), compaction, shear properties (cohesion and friction angle), and saturated hydraulic conductivity.

1. Since the base soils differed for TS1, it is difficult to comment on the amendment effects on PSD on TS1 treatments. However, in TS2 in which the control soil was amended with OM, results revealed that amendments increased the silt fraction of the control soil (CUT2) from 60.2% to 62%, 64.3%, and 62.1% for MAT2, LAT2 and BAT2 respectively while the sand fraction was decreased from 37.9% to 36.2%, 33.9%, and 36.2% for MAT2, LAT2 and BAT2 respectively. However, all soils fell under the category of silt loam.
2. Results from the compaction tests revealed that the maximum dry unit weight of the control soil in both tub studies was lower for amended soils as compared to the control soils.
3. Shear properties indicate that all the soils used in the tub studies are comparable to earthen materials. Compacting the soils at $w_{opt+3\%}$ reduced the overall shear strength of the soils as expected, even though differences in LAT and BAT treatments at w_{opt} and $w_{opt+3\%}$ are greater. Conclusions about how these differences could affect erosion potential cannot be determined at this time.
4. MAT soils had the highest hydraulic conductivities at $\gamma_{d,\ max}$ and γ_{tub} comparted to the other treatments in both tub studies, which means that mulch greatly affected saturated hydraulic conductivity of the soils.

6. RECOMMENDATIONS

1. SHA should establish standard protocols and methods for soil tests and reach out to local labs to communicate SHA protocols to ensure consistency between private labs and MDOT Office of Materials Technology (OMT).
2. SHA should have soil producers disclose the source of the organic matter amendment used in their topsoil, if any, when submitting soil samples. Additionally, soil test results should be considered in the context of the identified amendments.
3. To encourage wider usage of compost and compost-like products, SHA should consider adjusting furnished topsoil standards for pH and soluble salts, to match those of salvaged topsoils.
4. Information on the following parameters can be beneficial when added to SHA soil tests: *a)* C:N ratio; *b)* Total Nitrogen (to provide information on the nitrate supplying

capacity of the soil); *c)* Plant available N (to aid in decisions related to nutrient management plans).

5. Producer provided soil samples are beneficial for determining the QPL status. However, SHA should consider testing furnished topsoil once it arrives at a construction site for OM, soluble salts, pH, TN, available N, P, S, and the C:N ratio. Doing so will allow SHA control over the type of amendment used to raise %OM should furnished topsoil fall below the minimum specification. Additionally, if the pH falls outside of current specifications, a pH amendment can be applied onsite. Furthermore, N (refer to #4) and P results could be used to make informed decisions about nutrient management plans.
6. Because of the high C:N ratio of mulch materials, mulch amendments should not be used to raise the concentration of soil OM without a supplemental source of nitrogen to help reduce nitrogen deficiencies following the addition of mulch to topsoil.
7. Biosolids can be used to provide a wide range of essential plant nutrients to soils with nutrient deficiencies, especially those with N and micronutrient deficiencies. If and when using biosolids to raise the OM content of soil, due to potential high N losses, it should be used at a low rate or mixed with another low-N amendment.
8. Since runoff from biosolids-amended topsoil was negligible, this research demonstrates that biosolids can be used as an amendment on slopes equal to or less than 25:1 without contributing to high N concentrations in surface runoff. However, at inclines greater than 25:1, biosolids leachate could combine with surface runoff. Since these studies determined that biosolids significantly increase N concentrations in leachate, the risk of high runoff N concentrations could be greater at steeper inclines. SHA usage of biosolids should be restricted to slopes < 25:1 until further studies are conducted.

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APPENDIX A

SOIL PRODUCER INTERVIEW QUESTIONS

1. Where do you source your soil(s) from (location and/or company)? Could you give your top 5? If more than 5, please rank them.
2. Where do you source the organic matter/material(s) that you use (location and/or company)? Could you give your top 5? If more than 5, please rank them. If compost, what is the type/source of compost (biosolids, food waste, manure, etc.) you use?
3. What are the driving factors (cost, location, nutrient availability, texture, ease-of incorporation, other (please list) that determine which material is chosen? Could you rank these factors in order of importance?
4. What specific considerations do you take into account when adding organic materials (OM) to topsoil?
5. Given SHA's material specification guidelines, how do you meet your target OM percentage? How do you measure this (by volume or weight)?
6. How do you sample your final product? Do you send your samples to AgroLab? If not, who provides the nutrient and OM analysis for you? Do these lab results typically reflect your expectations?
7. Does the addition of compost to meet SHA's 4% by weight minimum affect other SHA soil requirements as outlined in the SHA Standard Specifications?
8. Do you think the soil analysis performed in accordance with SHA's Qualified Products List (QPL) adequately represents the topsoil that you produce? If not, why not?
9. Are you interested in receiving a summary or briefing of the results of this research?
10. Are you willing to provide a sample of furnished topsoil and/or individual topsoil components for research purposes to the University of Maryland?

COMPOST PRODUCER INTERVIEW QUESTIONS

1. How many products do you make? Which one(s) do you recommend for topsoil?
2. Do you make specific products for topsoil producers?
3. How would you describe your demand from topsoil producers? How do you manage it? Examples can include: “I manage it on a first come, first serve basis” and “I limit buyers to purchasing N/week.”
4. What are your stock components for each product?
5. Where do you source materials from? Do you have a hard time securing source material?
6. What are the driving factors (cost, location, nutrient availability, texture, ease-of incorporation, other (please list) that determine which material is chosen? Could you rank these factors in order of importance?
7. Do your components change throughout the year or do you have a consistent supply?
8. How might your product change throughout the year? What contributes to changes if they occur?
9. How do you sample your product? Do you have lot-analyses to ensure consistency or show variability?
10. Do you analyze organic matter content, soluble salts, and pH?
11. Do lab results typically reflect your expectations? If not, please explain.
12. Do you provide testing results to your clients?
13. If at all, how do you manage pH or soluble salts?
14. Are you interested in receiving a summary or briefing of the results of this research?
15. Are you willing to provide a sample for research purposes to the University of Maryland?

APPENDIX B

Protocol For Water (Leachate/Runoff) Sample Collection and Volume Measurement

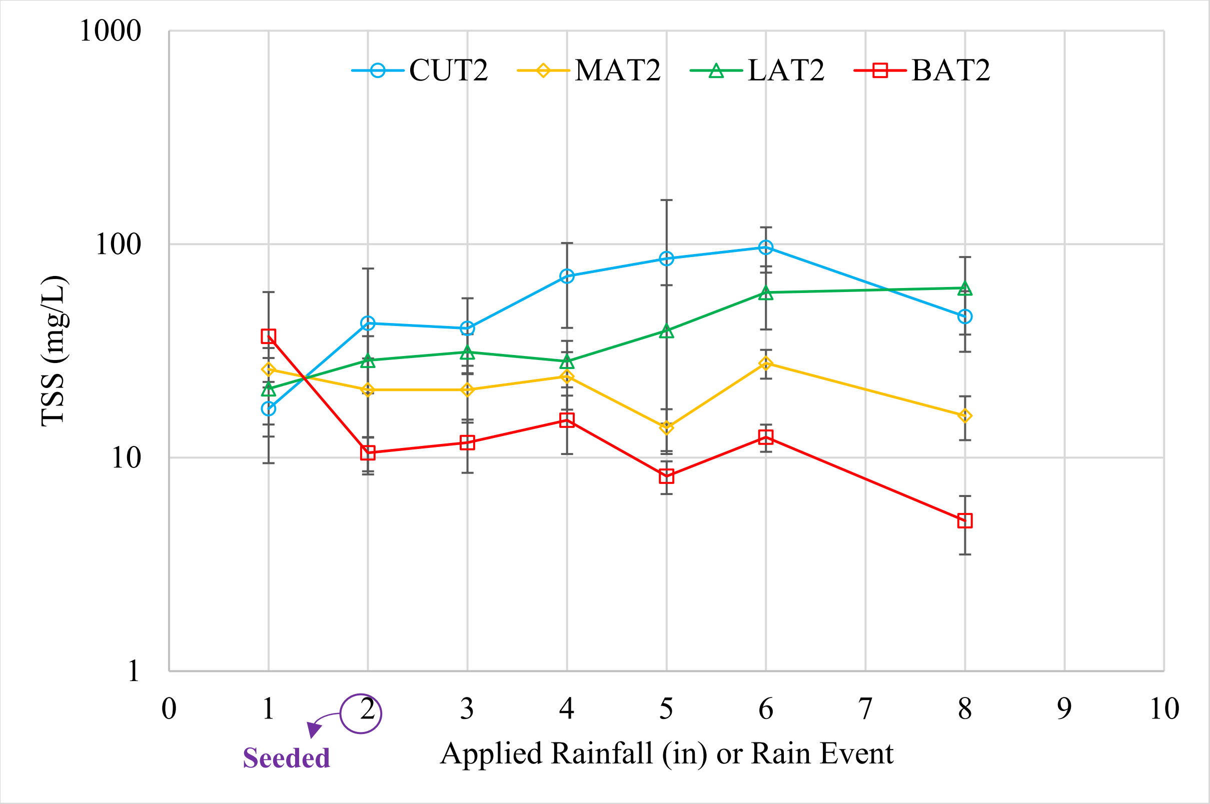
Materials:

1. Two graduated cylinders (plastic): 1000 ml and 500 ml
2. One pitcher with molded graduations (1000 ml)
3. 1-litre HDPE sample bottles
4. 1-gallon ziplock bags for backup sample storage
5. Two 5-gallon buckets for DI water rinses

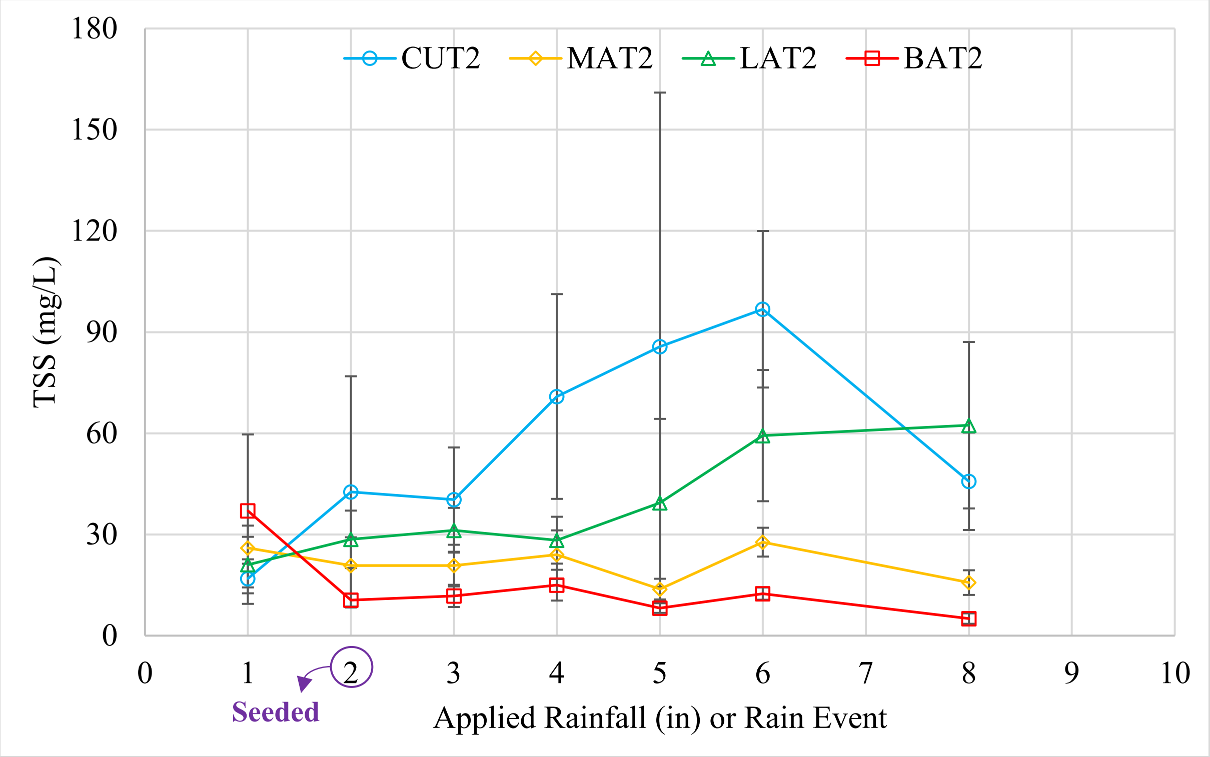
Collection Protocol:

1. Prior to sampling, label all the 1-liter sample bottles and the ziplock bags based on the number of samples collected according to the following format: Treatment type (CUT, MAT, LAT, BAT), Replicate # (1, 2, 3, 4), collection date and rain event #.
2. Always start with water samples that contain less sediment or particles.
3. In order to obtain a representative composite sample, the water inside the collection bucket should be stirred well before the water is scooped out for volume measurement.
4. Using a 1000 ml pitcher, scoop the well-mixed sample into the clean graduated cylinders to measure the leachate/runoff volume.
5. Once the volume is measured, transfer 1000 ml of the water sample into its respective sample bottle for immediate chemical analysis.
6. Transfer another 500 ml to 1000 ml of sample into its corresponding ziplock bag for backup purposes.
7. Rinse the graduated cylinders and the pitcher well with tap water and 2-DI waters between sampling different leachates.
8. Replace the DI water in the rinse buckets after every 7-8 samples, or after every 4-5 samples if the water samples are sediment dense.
9. After collecting all the samples, they will be ready for immediate chemical analyses testing.
10. Backup samples collected in the ziplock bags should be stored under freezing (-18 °C) conditions.

APPENDIX C



(a) TSS (mg/L) from TS1 soils



(b) TSS (mg/L) from TS2 soils

Fig. S1. *Mean concentrations of Total Suspended Solids (TSS) from treatments used in Tub Study 1 (TS1) and Tub Study 2 (TS2)*

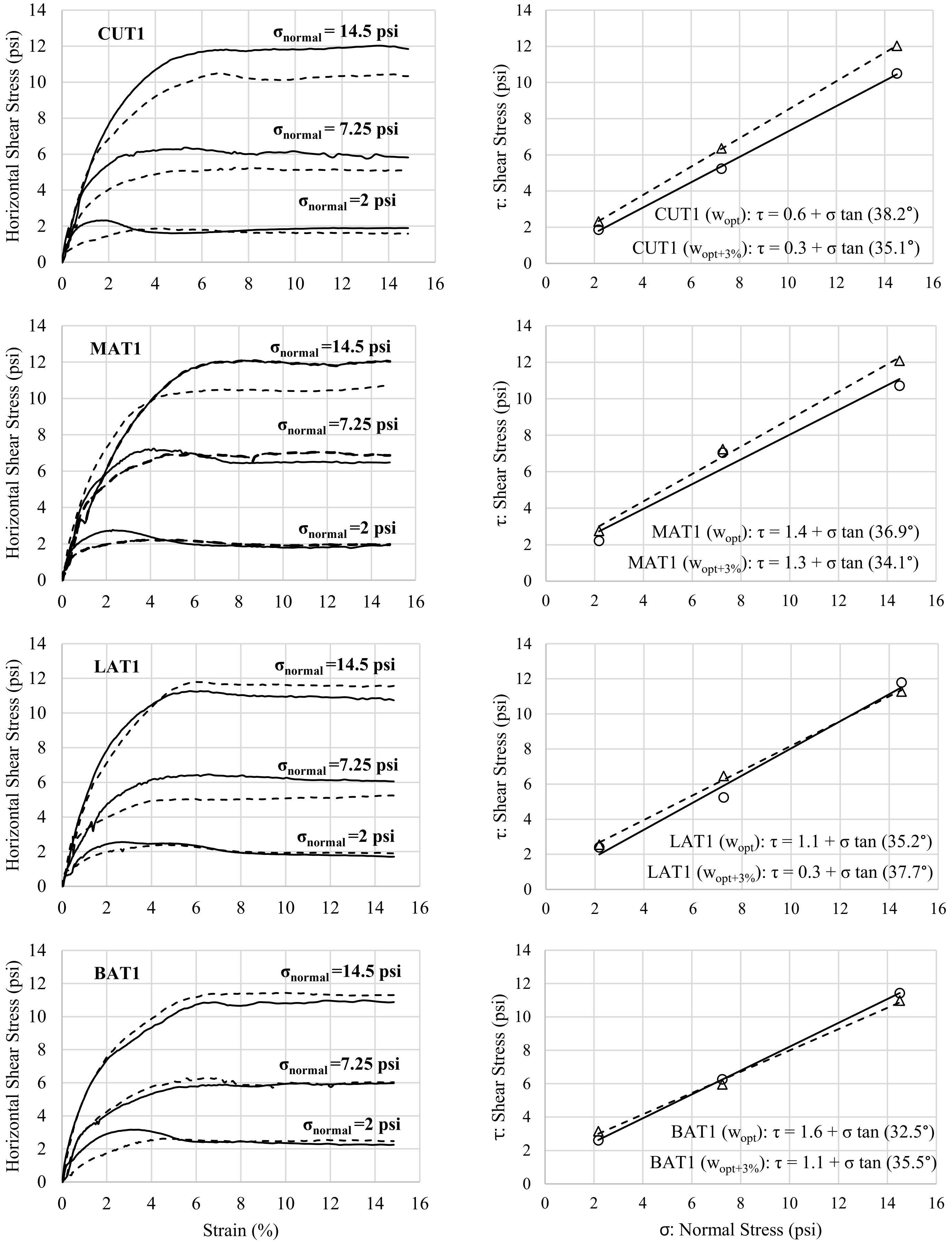


Fig. S2. *Direct shear plots: Stress vs Strain curves and Mohr-Coulomb Failure envelops of Tub Study 1 soils*

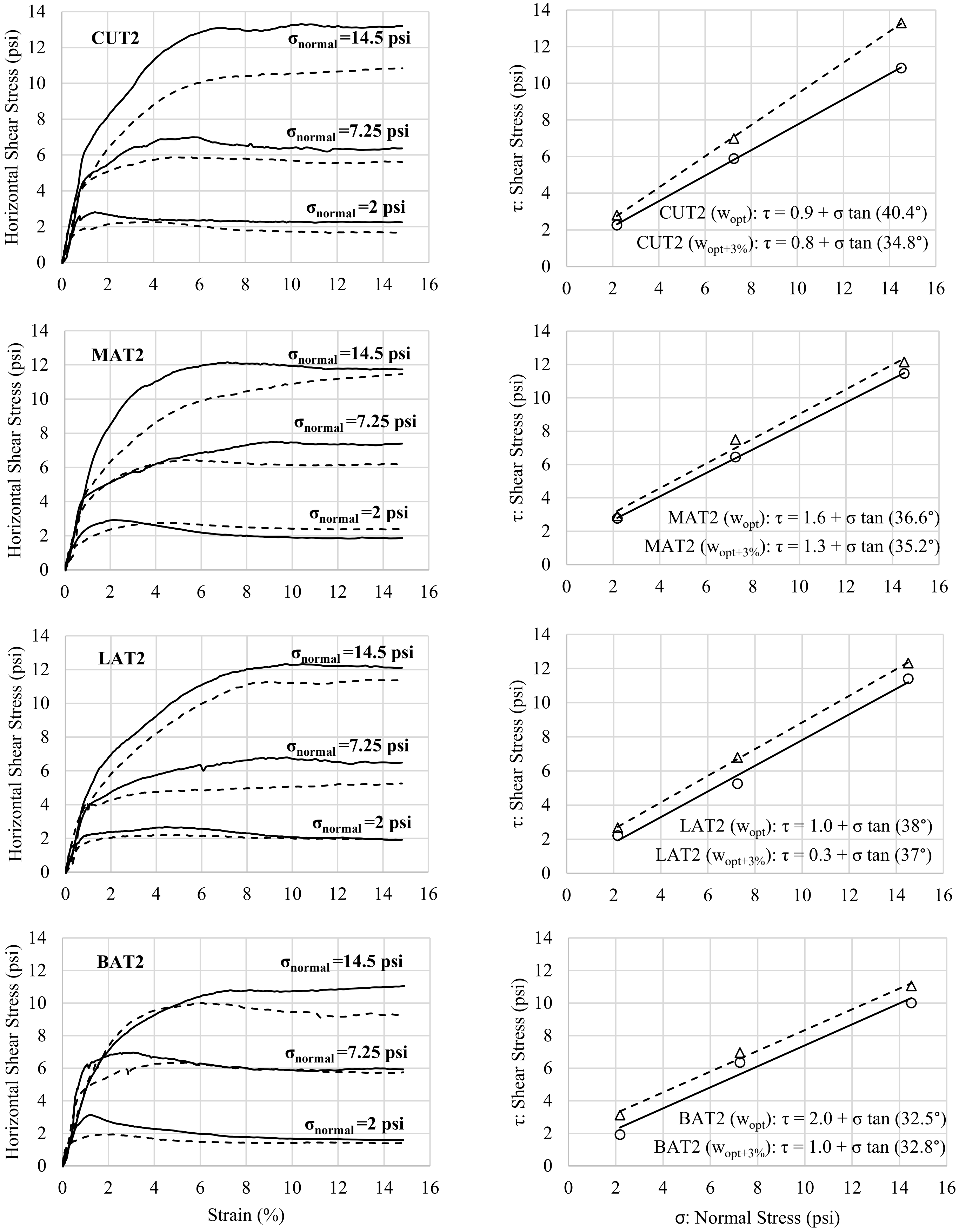


Fig. S3. *Direct shear plots: Stress vs Strain curves and Mohr-Coulomb Failure envelops of Tub Study 2 soils*

APPENDIX D

Plot used to determine the OM Addition to the Base Soil (CUT2) for Tub Study 2 Blends

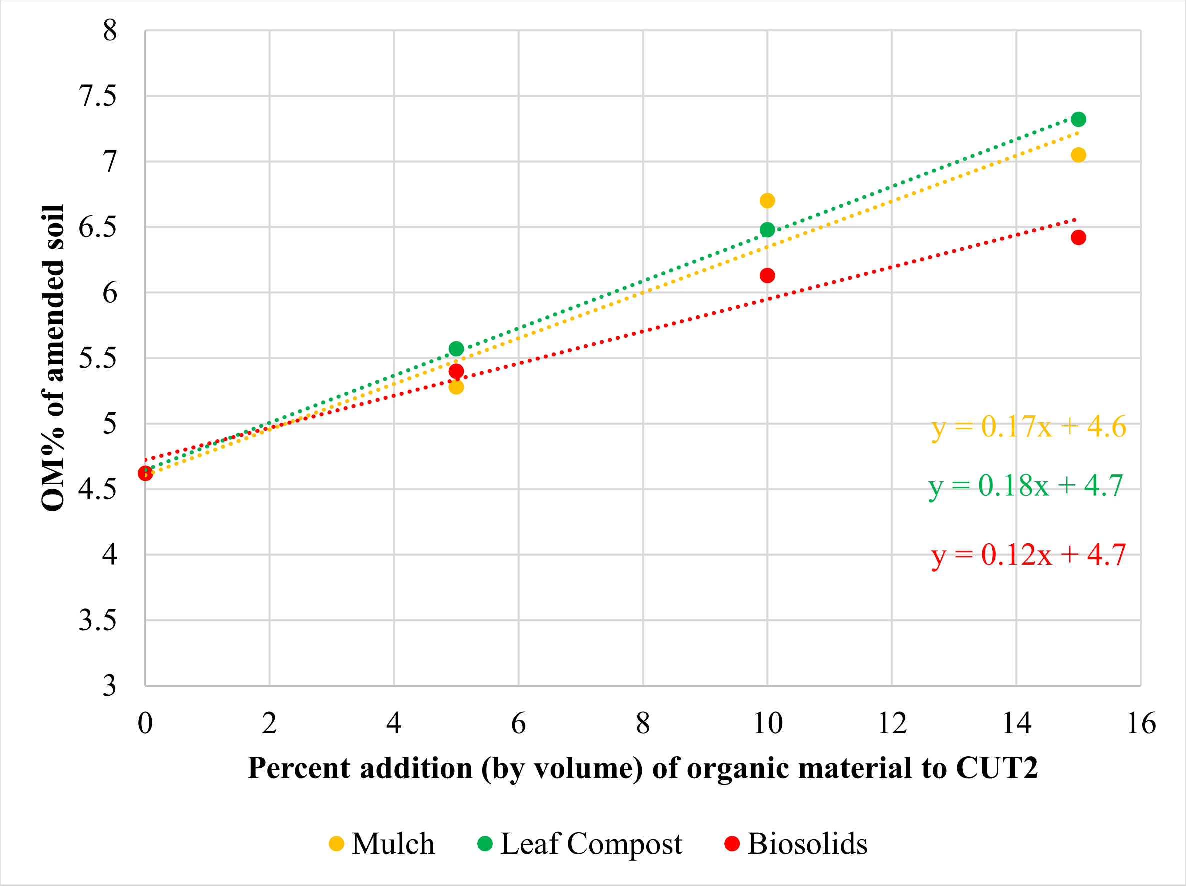


Fig. S4. *Percent addition of organic material to control soil (CUT2) on a volume basis (x) vs OM% of the amended soil (y)*

APPENDIX E

Analysis of Quarterly pH and OM Results for Furnished Topsoil

The following information represents a report by an undergraduate student, Mr. Daniel Oberholtzer, created to fulfill the requirements of an independent research study, under the direction of Ms. Jennifer Morash (PhD student) and Dr. John Lea-Cox..

This study evaluated data of furnished topsoil quarterly organic matter, pH, and soluble salts test results.

ANALYSIS OF MARYLAND STATE HIGHWAY FURNISHED TOPSOIL SPECIFICATIONS AND QUARTERLY ORGANIC MATTER, PH, AND SOLUBLE SALTS TEST RESULTS

By Daniel Oberholtzer

Introduction

Definitions:

According to Maryland Department of Transportation State Highway Administration's (SHA) *Standard Specifications for Construction and Materials* (2020), ***existing*** topsoil is defined as, "the surface material of existing landscaped areas on SHA property that will be used for seeding or other landscape construction without excavation or significant grading." SHA defines **salvaged** topsoil as "the surface material of existing landscaped areas on SHA property that will be used for seeding or other landscape construction after being excavated, stockpiled, and placed in designated areas." **Furnished** topsoil is defined as "a natural, friable, surface soil that is uniform in color and texture, and not derived from the project." Furnished topsoil is usually derived from contractors.

Current Standards:

Below in Table 1 are the current parameters (SHA standards) used for furnished topsoil and existing and salvaged topsoil with respect to soil pH, percent organic matter, and maximum soluble salt concentration.

Table 1. SHA Standards for Soil pH, Percent Organic Matter, and Max Soluble Salts for Existing & Salvaged Topsoil and Furnished Topsoil.

Composition Summary of Existing & Salvaged Topsoil and Furnished Topsoil

	Soil pH	%OM (by weight)	Max Soluble Salts (mmho/cm)
Existing & Salvaged Topsoil	4.8 - 7.6	1.0 - 8.0	1.25 (800 ppm)
Furnished Topsoil	6.1 - 7.2	4.0 - 8.0	0.78 (500 ppm)

The State of Maryland differentiates between furnished topsoil and existing & salvaged topsoil unlike other states in the Mid-Atlantic. States such as New York and Delaware do not have standards for soil pH, percent organic matter or maximum soluble salt concentration. Other states have more relaxed standards for percent organic matter concentration (%OM) such as Pennsylvania (2 – 10), Virginia (2 – 10) and West Virginia (1.5 - 20); but, these states do not have standards for maximum soluble salt concentration or pH. New Jersey does have standards for %OM (>2.75) along with pH (4.1 - 7.2). However, these standards are less restrictive than Maryland standards. The only locality with more restrictive standards in the Mid-Atlantic region is Washington D.C., with a pH range of 5.5 - 6.6, maximum soluble salt concentration of 500 ppm and a %OM range of 2 – 5.

Background:

Maryland House Bill 878 (H.B 878, 2014) was promulgated to review existing specifications on compost and compost-based products and develop new specifications to maximize the amount of compost in State highway construction. Maryland House Bill 878 states these new specifications are created to:

- Divert organic material away from landfills;

- Filter pollutants from surface runoff;
- Reduce erosion and turf loss;
- Provide jobs based on manufacturing compost and the application of compost;
- Compost material to degrade, immobilize or eliminate contaminants including: heavy metals, chlorinated and nonchlorinated hydrocarbons, pesticides, herbicides, wood preservatives and herbicides;
- Expand use of compost in landscaping, soil amendments, seeding and for erosion control, following the lead of other state highway and transportation agencies.

After the passage of HB 878 in 2014, the MDOT-SHA established a minimum concentration of 4% for OM in topsoil used on state highway projects to encourage more compost usage. SHA gradually phased in the new minimum, with enforcement of the new standard becoming effective at the end of 2019. The current SHA specifications restrict what soil can be used on State highway construction projects. Amending soil with OM is known to change the base soil pH (depending on maturity) and potentially the concentration of soluble salts in compost-amended topsoil (CAT) blends, depending on the type of amendment used (Hosseinpur & Paschamokhtari, 2013). Thus, adding OM may cause difficulties meeting other furnished topsoil specifications. In the early stage of composting, organic acids such as acetic acid and lactic acid are formed, reducing pH (Sundberg, 2005). As the compost matures, these acids are neutralized and the pH increases (Sundberg, 2005). Amendment in the soil can improve aeration of the soil and allow the soil pH to increase. Certain sources of organic matter may be high in soluble salts. For example, biosolids in amended soil are known to be high in soluble salt concentration (Hosseinpur & Paschamokhtari, 2013). Soluble salts draw away water from the plant roots and either individual salt, or total salt concentrations can be toxic to plants in excess (Gruttadaurio et al., 2013). These salts can be leached out of the soil over time, or with suitable pre-treatment techniques.

Topsoil producers are required to submit soil tests before their products are used for state highway remediation projects. When this research began, soil tests were submitted once a quarter by approved topsoil producers. Beginning in 2021, SHA loosened these requirements to every six months. The purpose of the tests is to ensure that the MDOT-SHA topsoil specifications are met. With these test results, trends in compliance with the pH, organic matter percentage and soluble salt specifications can be examined. They can also be used to determine if increasing the minimum concentration for organic matter in furnished topsoil has any effect on yearly pH or soluble salt concentrations.

Study Objectives:

An examination of historic producer soil tests was conducted to satisfy the following objectives:

- Determine if the addition of organic matter makes it more difficult to comply with SHA specifications for organic matter percentage, soil pH and max soluble salt concentration.
- Determine how many more samples would fall within minimum and maximum specifications for organic matter, pH and soluble salts, if furnished topsoil specifications were expanded in order to match current existing and salvaged topsoil standards.
- Determine if there is a correlation between organic matter and soil pH in order to better inform composition standards.

Methods

The Maryland Department of Transportation State Highway Administration received 95, 106, 107 and 52 furnished topsoil analyses from an independent (contracted) laboratory, AgroLab (Harrington, Delaware) for 2018, 2019, 2020 and 2021 respectively. In the 2021 soluble salt comparison, the soluble salt concentration data were missing from a majority of AgroLab samples. Instead, data from the MDOT Office of Materials Technology laboratory (OMT) were included in the analysis of soluble salts (sample size [N] =65). 2021 results from both AgroLab and OMT laboratory were available for quarter one, quarter two and quarter three.

An independent t-test was conducted on samples from AgroLab and OMT for %OM and soluble salt (SS) concentration for 2021. This was done to see if there was a statistically significant difference between the %OM and SS results between the two labs, to ascertain whether the OMT results could be included in the data set.

Furnished topsoil specifications are more restrictive than existing and salvaged topsoil. Comparisons of test results to determine differences between the ranges of pH, soluble salt concentration, and percent organic matter were performed and are individually described in the results. The analyses performed quantified test results based on furnished topsoil standards and standards meant for salvaged and existing topsoil.

Results

Lab Result Comparisons:

An independent t-test was performed to compare the 2021 %OM values between Agrolab and OMT. There was a statistically significant difference between %OM values where $t(112) = -5.89$ ($p < 0.01$). An outlier result of 13.1% was excluded from the AgroLab data. Likewise, an independent t-test was performed to compare the 2021 pH values between the two labs. Again, a statistically significant difference was found between pH values where $t(115) = 2.86$ ($p < 0.01$). These results are summarized in Table 2.

Table 2. T-test Performed on the pH and Percent Organic Matter Values between Agrolab and OMT Furnished Topsoil Analyses

	AgroLab Mean (SD)	**OMT Mean (SD)**
Organic Matter	3.90 (1.52)	5.36 (1.28)
pH	7.12 (0.54)	6.85 (0.47)

pH Results:

Sample pH was compared to the SHA standard in the following manner, including samples that:

- met furnished topsoil specifications (6.1 - 7.2);
- those below furnished topsoil specifications, but still within existing & salvaged topsoil specification (4.8 - 6.0);
- those above furnished topsoil specifications, but still within existing & salvaged topsoil specifications (7.3 - 7.6);
- those below both specifications (< 4.8);
- those above both specifications (> 7.6); and
- those above furnished topsoil specifications (> 7.6).

A one-way between subjects ANOVA was conducted with alpha 0.05 to compare the data between years for pH. The results are summarized in Figure 1. There was a significant effect for pH based on the four years. [$F(3, 356) = 12.062$, $P < 0.01$]. Post hoc comparisons using the Bonferroni test indicated that the mean for 2018 (Mean = 6.63, SD = 0.77) was significantly different than 2020 (Mean = 7.10, SD = 0.62). Similarly, post-hoc comparisons also indicated that the mean for 2018 was significantly different than 2021 (Mean= 7.12, SD = 0.54); and the mean for 2019 (Mean = 6.77, SD = 0.63) was significantly different from the 2020 (Mean = 7.10, SD = 0.62) and 2021 (Mean = 7.12, SD = 0.54) results. These statistical differences are noted using superscript letters in Table 3. The mean and median pH was also determined for the 2018 - 2021 samples. Results are summarized in Table 3.

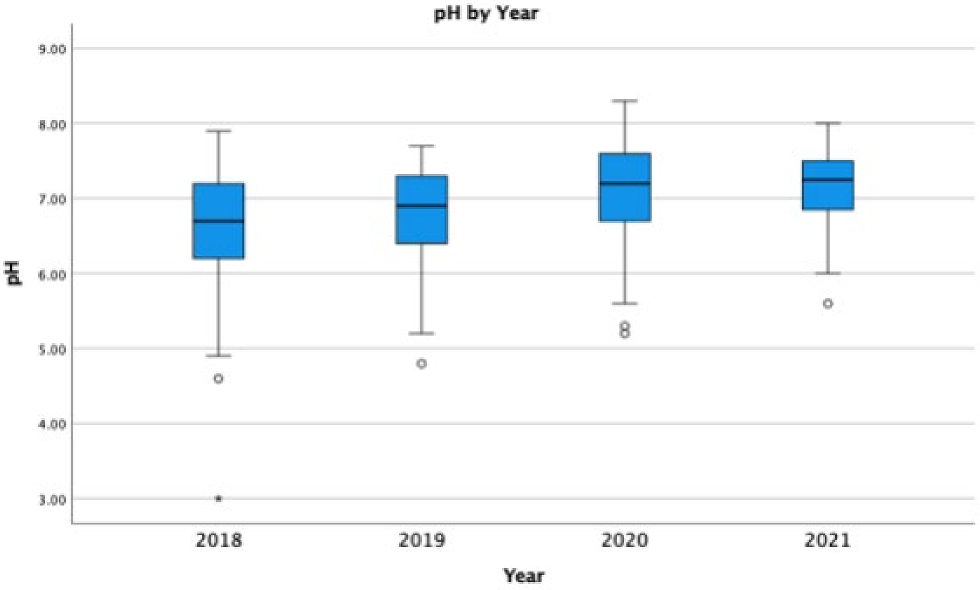


Figure 1. Box Plot of pH data from years 2018 – 2021

Table 3. pH Range Comparison to SHA Standards of Samples for 2018 - 2021.

Number of Samples to Fall Within the Following pH Ranges Sample Size (N) and (%)						**Mean/Media pH for Samples (N)**	
Year	**< 4.8**	**4.8 - 6.0**	**6.1 - 7.2**	**7.3 - 7.6**	**> 7.6**	**Mean** [#]	**Median**
2018 **(N = 95)**	2 (2.10%)	14 (14.74%)	57 (60.00%)	18 (18.95%)	4 (4.21%)	$6.63^{a, b}$	6.70
2019 **(N = 106)**	0 (0%)	15 (14.15%)	64 (60.38%)	25 (23.58%)	2 (1.89%)	6.77^{c}	6.90
2020 **(N = 107)**	0 (0%)	6 (5.61%)	52 (48.59%)	27 (25.23%)	22 (20.56%)	$7.10^{a,c}$	7.20
2021 **(N = 52)**	0 (0%)	2 (3.85%)	24 (46.15%)	19 (36.54%)	7 (13.46%)	$7.12^{b,c}$	7.25

Key: Number of samples outside both existing/salvaged and furnished topsoil standards (Blue); Outside furnished topsoil standards but within existing/salvaged topsoil standards (Yellow), and within both existing/salvaged and furnished topsoil standards (Green).

[#] One-way ANOVA showed significant differences at $p < 0.01$. Superscript letters denote significant differences in mean values when alpha = 0.05.

Soluble Salt Results:

Sample soluble salt concentrations were compared to the SHA standard in the following manner, with samples that:

- met furnished topsoil specifications (≤ 0.78);
- were above furnished topsoil specifications, but still within existing & salvaged topsoil specification (0.79 - 1.25); and
- were above both specifications (> 1.25).

The mean and median Soluble Salt Concentration was determined for 2018 - 2021 samples. The results are summarized in Table 4. Additionally, a one-way between subjects ANOVA was conducted (alpha = 0.05) to compare the data between years for soluble salt concentration. Differences between means (years) were not significant.

Table 4. Soluble Salt Concentration Range Comparison to SHA Standards of Samples for 2018 - 2021.

Number of Samples to Fall Within the Following Soluble Salt Concentration Ranges Sample Size (N) and (%)				**Mean/Median Soluble Salt Concentration (mmho/cm)**	
Year	**≤ 0.78**	**0.79 - 1.25**	**> 1.25**	**Mean**	**Median**
2018 **(N = 95)**	92 (96.84%)	2 (2.11%)	1 (1.05%)	0.26	0.19
2019 **(N = 106)**	104 (98.11%)	0 (0%)	2 (1.99%)	0.29	0.24
2020 **(N = 107)**	104 (97.20%)	2 (1.87%)	1 (0.93%)	0.28	0.22
2021 **(N = 65)**	65 (100%)	0 (0%)	0 (0%)	0.29	0.25

Key: Number of samples outside both existing/salvaged and furnished topsoil standards (Blue); Outside furnished topsoil standards but within existing/salvaged topsoil standards (Yellow), and within both existing/salvaged and furnished topsoil standards (Green)

Organic Matter Results

Sample pH's were compared to the SHA standard in the following manner, including samples that:

- met furnished topsoil specifications (4.0 - 8.0%);
- those below furnished topsoil specifications, but still within existing & salvaged topsoil specifications (1.0 - 3.9%);
- those below both specifications (< 1.0%);
- those above both specifications (> 7.6%); and
- those above furnished topsoil specifications (> 8.0%).

The mean and median organic matter percentage was determined for the 2018 - 2021 samples. Results are summarized in Table 5. A one-way between subjects ANOVA was conducted (alpha = 0.05) to compare the data between years for percent organic matter. Differences between means (years) were not significant.

Table 5. Comparison of Organic Matter Percentages to SHA Standards, for Samples from 2018 - 2021.

	Number of Samples to Fall Within the Following % Organic Matter Ranges Sample Size (N) and (%)				**Mean/Median % Organic Matter**	
Year	**< 1.0**	**1.0 - 3.9**	**4.0 - 8.0**	**> 8.0**	**Mean**	**Median**
2018 (N = 95)	0 (0%)	52 (54.74%)	43 (45.26%)	0 (0 %)	4.13	3.7
2019 (N = 106)	0 (0%)	62 (58.49%)	42 (39.62%)	2 (1.89%)	3.94	3.45
2020 (N = 107)	1 (0.93%)	58 (54.21%)	45 (42.06%)	3 (2.80%)	3.92	3.60
2021 (N = 52)	0 (0%)	31 (59.61%)	19 (36.54%)	2 (3.85%)	4.06	3.55

Key: Number of samples outside both existing/salvaged and furnished topsoil standards (Blue); Outside furnished topsoil standards but within existing/salvaged topsoil standards (Yellow), and within both existing/salvaged and furnished topsoil standards (Green).

Multivariate Analyses

A linear regression was performed to determine if OM significantly predicts pH. The fitted regression model for samples collected between 2018 and 2021 was: $y = 0.0424x + 6.6622$. The result is summarized in Figure 2. Figures 3 - 5 summarize individual comparisons for 2018, 2019, and 2020 respectively.

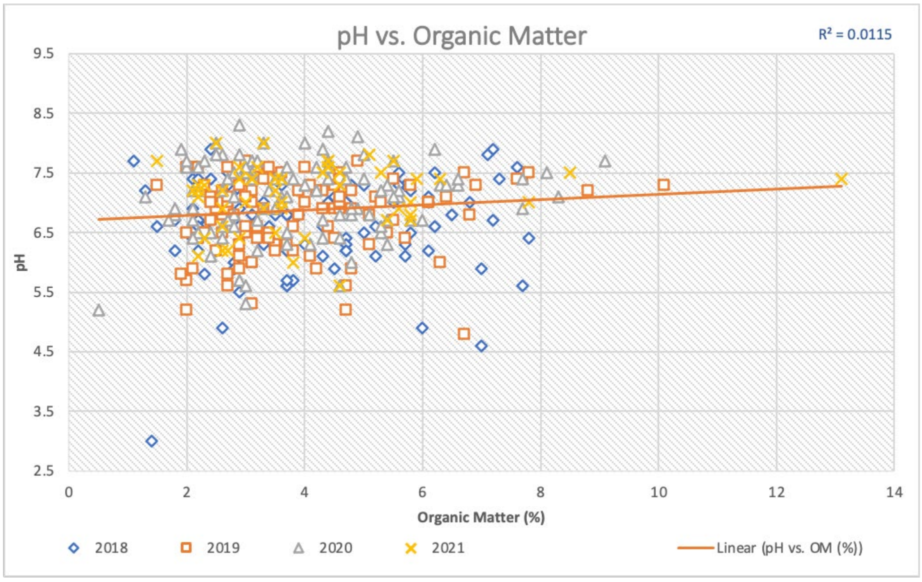


Figure 2. pH vs Organic Matter Percentage Graph of Samples for 2018 - 2021.

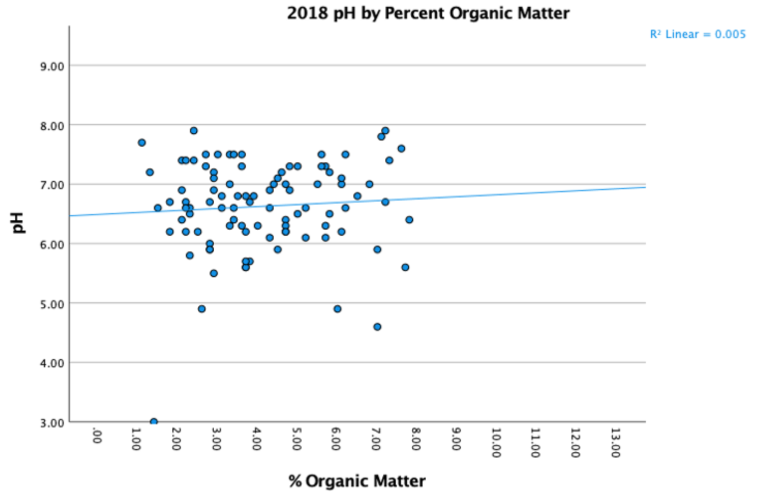


Figure 3. pH vs Organic Matter Percentage Graph of Samples for 2018. (P = 0.479)

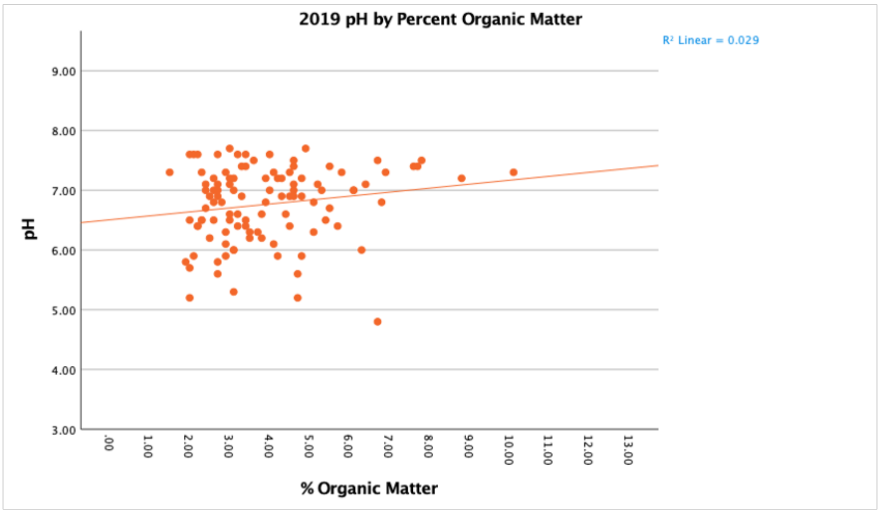


Figure 4. pH vs Organic Matter Percentage Graph of Samples for 2019. (P = 0.079)

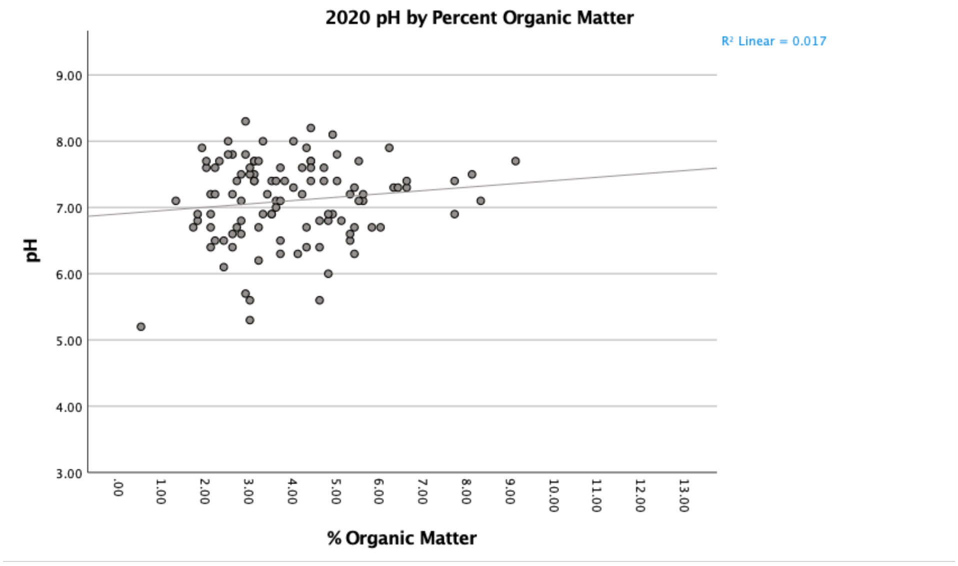


Figure 5. pH vs Organic Matter Percentage Graph of Samples for 2020. (P = 0.184)

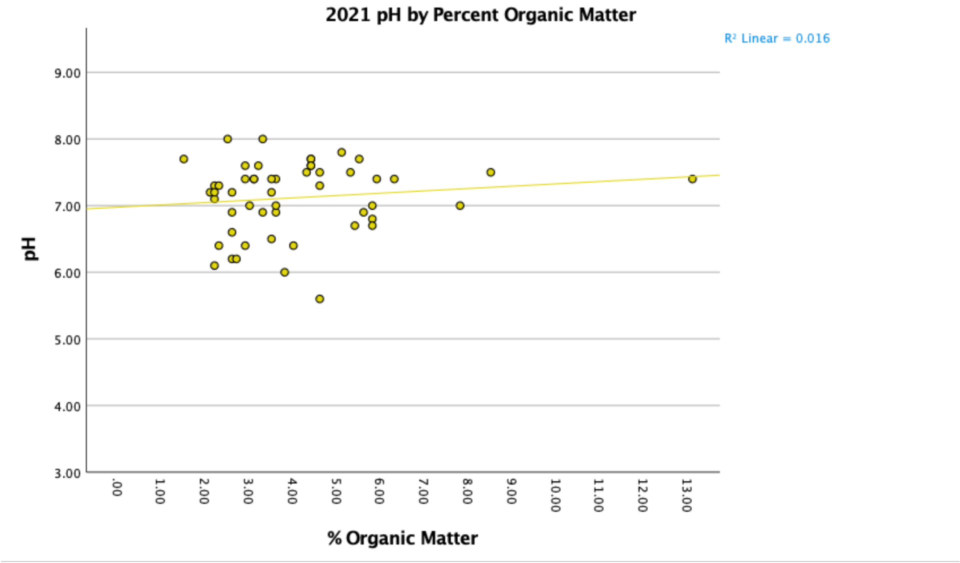


Figure 6. pH vs Organic Matter Percentage Graph of Samples for 2021. (P = 0.367)

Discussion

Organic Matter Analysis: There were few differences in %OM contents between the four years. The most pronounced observation is that the majority of samples were below furnished topsoil standards in all four years, but still within existing and salvaged topsoil standards. This reveals that a majority of topsoil producers are not meeting furnished topsoil standards with the current specifications. There were no significant differences between the mean percent organic matter concentration over the four years. What is notable is that the mean %OM for 2019 and 2020 are below furnished topsoil specifications (Table 5). Table 5 also shows that the median of the soil samples is below furnished topsoil standards for all four years. **These results indicate that raising the minimum OM concentration may not have resulted in increased compost usage.**

pH Analysis: In 2018 and 2019, more soil producers met furnished topsoil standards (60% and 60.38% respectively) compared to 2020 and 2021, with only 48.59% and 46.15% respectively who met furnished topsoil standards. There was a notable shift in the number of samples that fell below furnished topsoil standards but still within existing and salvaged topsoil standards. In 2018 and 2019, more soil producers were below furnished topsoil standards, but still within existing and salvaged topsoil standards (14.74% and 14.15% respectively) compared to 2020 and 2021, with only 5.61% and 3.81% respectively in this range. This corresponds to the increase in the number of samples in 2020 and 2021 being above both standards. **Even with more samples achieving specified standards in 2020 and 2021, the results (Table 3) indicate that expanding pH furnished topsoil specifications to encompass existing and salvaged topsoil specifications would include an additional 30-40% of total soil sampled.**

Figures 2 – 6 show that there is weak or no correlation between pH and %OM. This indicates that current %OM levels in the furnished topsoil have little effect on the pH of the soil. However, there is little indication that compost addition has increased with the introduction of a new %OM minimum.

Soluble Salt Analysis: Each year, a vast majority of samples that fell below the max soluble salt concentration for furnished topsoil, which is 0.78. Even though existing and salvaged standards are less restrictive than furnished standards, the majority of all test results fell below the standards for furnished topsoil. There were no significant differences between the mean soluble salt concentrations over the four years. **The results indicated that soil producers do not have issues meeting the soluble salt standards. Therefore, the amendments currently used to meet the minimum OM standards should have few effects on raising the soluble salts concentrations above the maximum limit for furnished topsoil (0.78 mmhos/cm).**

Conclusions

A comparison of the quarterly SHA soil test for 2018-2021 indicates that in order to have more soil producers amending compost into furnished topsoil, the standards of pH for furnished topsoil could be expanded in order to encompass existing and salvaged topsoil standards with few effects.

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