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Using organic amendments in disturbed soil to enhance soil organic matter, nutrient content and turfgrass establishment

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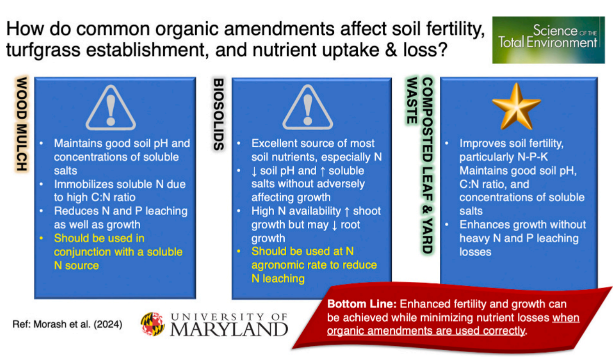
HIGHLIGHTS

- Organic amendment effects on soil properties and growth measurements of significance to landscape managers were analyzed.
- Composted leaf & yard waste can enhance turfgrass establishment, but caution is advised when using mulch or biosolids.
- Mulch raised soil organic matter but nutrient immobilization reduced turfgrass growth.
- Biosolids increased soil nutrients, growth, and N leachate losses.
- Recommendations for correct use of organic amendments are discussed.

GRAPHICAL ABSTRACT



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ABSTRACT

Disturbed soils, including manufactured topsoils, often lack physical and chemical properties conducive to vegetation establishment. As a result, efforts to stabilize disturbed soils with vegetation are susceptible to failure. Urban organic waste products such as wood mulch, composted leaf and yard waste, and biosolids are widely distributed as organic amendments that enhance sustainability and plant establishment. Correct use can be determined by examining soil properties such as pH; the concentration of soluble salts (SS); and plant available nutrients — particularly N, C and P; as well as root and shoot growth. This research examined the effects of three typical organic amendments on fertility, establishment, and nutrient loss. A manufactured topsoil was used as the base soil for all treatments, including a control unamended soil (CUT), and soil amended with either mulch (MAT), composted leaf and yard waste (LAT), or biosolids (BAT). A 2 % organic matter concentration increase was sought but not achieved due to difficulty in reproducing lab results at a larger scale. Results showed that LAT improved soil fertility, particularly N-P-K concentrations while maintaining a good C:N ratio, pH, and SS concentration. BAT was the most effective at enhancing shoot growth but results suggest that improved growth rates could result in increased maintenance. Additionally, biosolids were an excellent source of nutrients, especially N-

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P-K and S, but diminished root growth and N leachate losses indicate that N was applied in excess of turfgrass requirements. Therefore, biosolids could be used as fertilizer, subject to recommended rates for turfgrass establishment to prevent poor root growth and waterborne N pollution. To ensure establishment efforts are successful, MAT is not recommended without a supplemental source of soluble N. Altogether, study results and conclusions could inform others seeking to improve specifications for disturbed soil where turfgrass establishment is needed to stabilize soil.

1. Introduction

Establishing a robust vegetative groundcover on disturbed soil is a key strategy for controlling stormwater and soil erosion following major earthmoving operations like road construction. Such activities can negatively impact soil quality, thereby diminishing plant establishment and coverage (Zhao et al., 2007; Trammell et al., 2011). As a result, landscape managers, including governmental organizations, seek options for enhancing vegetation through soil improvements. Organic matter (OM) improves soil fertility by enhancing soil physical properties (e.g., bulk density, porosity, aeration, and water holding capacity) and by increasing the availability of nutrients through addition, pH improvements, and greater cation exchange capacity (Diacono and Montemurro, 2011; Dunifon et al., 2013; Schmid et al., 2017; Ferreiro et al., 2020). Numerous studies have shown that organic amendments, rich in OM, increase germination and vegetative coverage along roadsides (Evanylo et al., 2000; Reinsch et al., 2007; Pengcheng et al., 2008; Brown and Gorres, 2011; Fava, 2016; Ferreiro et al., 2020; Owen et al., 2021). Positive growth results along with increased interest in sustainable landscape management options indicate that the use of organic amendments in disturbed topsoil is bound to increase. Understanding differences in nutrient content and availability will help landscape managers achieve desired outcomes while minimizing unnecessary losses.

The fertilizer value of organic amendments varies by product and requires an understanding of nutrient content and availability. Balancing near- and long-term nutrient requirements calls for a temporal understanding of how nutrients are released from OM when organic amendments are used. For example, nitrogen mineralization is complicated and depends on a multitude of factors including temperature, moisture, time, and the carbon-to-nitrogen (C:N) ratio (Jansson and Persson, 1982). When the N concentration in OM does not meet the needs of a growing population of microbes, N is taken out of the soil solution, rendering it temporarily unavailable for plant uptake in a process called immobilization. Products that are fully composted generally release nutrients slowly over time, stretching plant benefits over multiple seasons (Sullivan et al., 1998). Conversely, some organic amendments (e.g., wastewater biosolids) may provide soluble nutrients, especially NO_3^- and ammoniacal-N (NH_4^+), immediately following incorporation (Rigby et al., 2016). Understanding nutrient differences, coupled with proper selection of organic amendments to affect short- and long-term nutrient dynamics, could help managers enhance vegetation establishment while reducing fertilizer use, maintenance costs, and unnecessary nutrient losses.

The fertilizer value of nitrogen (N) is usually the primary consideration when using organic amendments as nutrient sources for turfgrass, a typical groundcover in managed landscapes. This is because N is a critical factor in turfgrass establishment and is generally needed in the greatest amount (Mola et al., 2011; Hopkinson et al., 2016). Jimenez et al. (2013) demonstrated that early establishment of vegetation on newly constructed road slopes is highly associated with nitrate-N (NO_3^-) and OM during the first two years, but Geng et al. (2014) later showed that turfgrass growth responses eventually plateau at increasing concentrations of NO_3^-. These studies, along with evidence that mass losses of N leachate from turfgrass stands are positively related to N application rates (Wu et al., 2010), suggest that N additions should be limited by the capacity of vegetation to immobilize soluble N.

Although N is regarded as the primary factor in determining the success of turfgrass establishment, an adequate supply of phosphorus (P) is influential (Petrovic et al., 2005). Like N, the P content and availability of organic amendments can vary considerably and is dependent on the feedstock (Irene Torri et al., 2017). Generally, organic amendments composed primarily of animal wastes, including human waste, have high P concentrations. Therefore, use of biosolids as a source of OM or N may result in contamination of surface water with soluble and particulate P (Torri and Cabrera, 2017). Even so, much of the P in biosolids may be unavailable for plant uptake if it is bound to inorganic constituents, such as iron (Fe), aluminum (Al), and calcium (Ca). Potassium (K), is needed in large quantities compared to P; but unlike P, K is susceptible to leaching. Even though K is usually found in low concentrations in organic amendments, as compared to mineral sources, OM additions help to retain K by increasing the cation exchange capacity (CEC) of soil (Hue and Silva, 2000).

Overwhelmingly, fertilizer recommendations are based on the macro-nutrients N, P, and K; but a host of nutrients are responsible for optimizing vegetative growth. Other nutrients are required in small quantities and excesses or deficiencies can have large impacts on health and growth (Langridge, 2022). Soluble salts (SS) refer to inorganic soluble anions and cations, many of which are essential plant nutrients like NO_3^-, PO_4^{3-}, SO_4^{2-}, NH_4^+, Ca^{2+}, Mg^{2+}, and other non-plant-essential ions like Al^{3+} and Na^+. Sources include OM and fertilizers (Gondek et al., 2020). Excessive concentrations of SS in soil, especially Na^+ and Cl^-, can reduce germination, plant vigor, and cause plant injury (Parihar et al., 2015). However, others such as K^+, Ca^{2+}, SO_4^{2-}, and NO_3^- promote soil fertility and vegetative growth. Several studies conclude that organic amendments make ideal fertilizers for nutrient-poor soil due to measurable quantities of macro- and micronutrients (Richards et al., 2011; Zhang et al., 2015; Anees et al., 2016).

Hopkinson et al. (2016) provides key insights for managing topsoil in areas where cool season grasses are used to control erosion. In the study, 29 right-of-way sites in West Virginia were evaluated, to identify factors that contributed to vegetation quality and coverage. The following conclusions were drawn from the research findings: (1) Nitrogen was the only macronutrient that had a significant positive correlation with vegetation cover (correlation coefficient, $r = 0.52$). (2) The concentration of OM and vegetation cover was also positively correlated, but to a lesser degree ($r = 0.50$). (3) The concentration of SS had the greatest effect on cover, but the relationship was negative ($r = 0.67$). Specifically, the data showed that locations with the worst cover (i.e. below 50 %), had SS concentrations between 0.36 and 1.54 mmhos/cm or OM values below 1.7 %. Sixty-nine percent of sites had "less than optimal" OM levels, which were defined as <2 %. Vegetation cover was below 50 % for the vast majority of sites with soil pH <5 and >8. Holistically, the Hopkinson et al. (2016) study suggests that organic amendments can increase the quality and coverage of roadside vegetation, but it was dependent on other factors. In other words, organic amendments that increase soil OM, supply nutrients — particularly N, and positively affect soil pH, will likely enhance growth. However, organic amendments that raise the SS concentration of soils or drive the pH range outside of 5–8, can negatively impact vegetative establishment.

Landscape managers, including transportation authorities, may consider establishing targets and/or specifications for select soil properties to enhance vegetation establishment on disturbed soil. Choosing parameters is challenging when organic amendments are used, given the number of factors that affect growth and nutrient availability. Furthermore, desired soil properties will likely be determined by the type of vegetation chosen to stabilize disturbed soil. For example, Table 1 demonstrates the variability in topsoil pH, SS, and OM standards for highway right of ways throughout the mid-Atlantic region of the U.S., where cool-season turfgrasses are commonly selected for stabilization (Christians and Engelke, 1994).

For landscape managers contemplating ideal soil parameters for amended soil, the Maryland Department of Transportation State Highway Administration (MDOT SHA) provides benchmarks worth evaluating. This is because the minimum OM requirement for furnished topsoil (4 %, determined by loss on ignition) may drive topsoil dealers to add OM to soil bound for MDOT SHA jobsites (Morash, 2024). Furnished topsoil is defined as a natural, friable, surface soil that is uniform in color and texture. It is not derived from the project and is trucked in from offsite, as is often the case following construction activities ("Standard Specifications for Construction and Materials,", 2023). Previous research determined that uncomposted, finely-shredded, wood mulch or composted leaf and yard trimmings are likely to be used as soil amendments to meet MDOT SHA's furnished topsoil OM standard due to the products' availability, cost, and effects on soil pH and SS (Morash, 2024). Conversely, soil dealers expressed hesitancy in using biosolids to raise soil OM even though they too are widely available. Concerns included, but were not limited to, complying with the pH and/or SS specifications when biosolids amendments are used to raise soil OM.

This research was designed to inform landscape managers seeking to improve the fertility of disturbed soil through the use of organic amendments — specifically mulch, composted leaf/yard waste, and biosolids. Objectives included: (1) to compare three amended soils and one unamended soil for differences, if any, in soil fertility before and after a typical establishment period; (2) to compare turfgrass establishment by measuring root and shoot growth to assess the effects of three organic amendments on vegetation establishment; and (3) to compare the amount of N and P assimilated into biomass or lost through leaching to determine if nutrient applications were in excess of turfgrass establishment requirements. Discussion of leachate nutrient concentrations and forms associated with the experiment described below are presented in Pamuru et al. (2024). The same manuscript also details the effects of amendments on soil physical properties. Note that the treatments referred to as CUT, MAT, LAT, and BAT in this manuscript correspond to CUT2, MAT2, LAT2, and BAT2 in Pamuru et al. (2024).

2. Materials and methods

2.1. Soil and amendments

In Fall 2021, a single-factor microcosm (tub) study (TS) was conducted at the UMD greenhouse complex in College Park, MD. Microcosms were constructed from 51 × 74 × 18 cm, clear, flat-bottom plastic tubs. Each was filled with soil to a depth of 10.2 cm. Treatments included the manufactured control/unamended topsoil (CUT) and three amended manufactured topsoils. Amended soils were comprised of CUT and either finely shredded wood mulch (mulch amended topsoil: MAT), composted leaf and yard waste (LAT), or biosolids (BAT). The composted leaf/yard waste and biosolids used in the study were sold under the trade names Leafgro® (Maryland Environmental Service; Millersville, MD) and Fresh Bloom® (Blue Plains Advanced Wastewater Treatment Plant; Washington, DC), respectively. Fresh Bloom® is an EPA Class A EQ biosolids product, which is produced through anaerobic digestion. Digestion was preceded by thermal hydrolysis and followed by dewatering.

Analysis (described below) determined that the OM concentration of CUT was ~4 %. A 2 % increase was sought for the amended soils. To achieve this, several combinations of topsoil and organic materials were blended (based on volume) and analyzed for OM content. Then, a linear regression analysis was performed for each treatment using data points plotted by percent OM vs percent addition. Details are included in the supplemental material section. The volume of amendment needed for each treatment was: 8.0 %, 7.5 %, and 10.4 % for mulch, composted leaf/yard waste, and biosolids. The volume of amended soil needed to fill each microcosm to a depth of 10.2 cm was 38.3 L. Therefore 3.06 L, 2.08 L, and 3.98 L of mulch, composted leaf yard waste and biosolids were added to each microcosm, respectively. Soil and amendments were measured and mixed by hand on a clean surface, until amendments were evenly distributed as determined by visual inspection. Prepared tubs were filled to a depth of 10.2 cm with the four treatments (n = 16, 4 replicates/treatment). Microcosms were randomized by treatment on three benches within the greenhouse. Bench assignments were checked to ensure that treatments were evenly distributed among benches and along design edges. Supplemental fertilizer was not applied.

2.2. Tub study design

The design of the microcosms permitted subsurface leachate and surface runoff to be collected separately (when they occurred) in individual clean 22.7 L plastic collection buckets. To prevent accumulation of standing water, each microcosm was shimmed at the tub base to create a 25:1 slope, which allowed water to runoff if the simulated rainfall rate exceeded the infiltration rate. Removable rain simulators were constructed from tubs identical to the microcosm tubs and were suspended at 25 cm above the microcosms during simulated rain events (SRE). To provide equal rainfall intensity over the surface of the microcosms, 18–21 holes (1 mm) were randomly drilled into the plastic tubs. Drainage time for each rain simulator was measured to ensure consistency. A picture of a microcosm and rain simulator are included in the supplemental material.

Each tub was seeded with the MDOT-SHA specified cool-season turfgrass seed mix used for permanent soil stabilization (Newsome Seed; Fulton, MD). It consisted 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 %) ("Standard Specifications for Construction and Materials,", 2023). Seeds were applied at the specified rate of 224 kg·ha^{-1} (8.32 g/tub). After seeding, 1 kg·ha^{-1} of straw was sprinkled over treatment surfaces to help disperse water falling from the rain simulators. The microcosms were seeded on September 13, 2021 and harvested eight weeks later on November 8, 2021.

Two SREs were applied one week apart before seeding the microcosms to mimic a worst-case scenario — heavy rainfall immediately following amendment incorporation. After seeding, weekly SREs continued for the duration of each experiment. Altogether, nine SRE's were applied. The total amount of simulated rainfall applied was commensurate with the average expected for the area where the

Table 1
Specifications for pH, total soluble salts (SS), and organic matter (OM) content in topsoil as determined by Mid-Atlantic Departments of Transportation agencies. Data was acquired from online copies of each state's standard specification manual for road construction materials. A dash indicates that no standard was specified.

State		pH	Maximum SS	% OM	Last updated
New York		-	-	-	2019
New Jersey		4.1–7.2	-	> 2.75	2019
Pennsylvania		-	-	2–10	2024
Delaware		-	-	-	2022
Maryland[a]	S:	4.8–7.6	1.25 mmhos/cm	1–8	2023
	F:	6.1–7.4	0.78 mmhos/cm	4–8	2023
D.C.		5.5–6.6	1.00 mmhos/cm	2–5	2020
Virginia		5.5–7.0	-	2–10	2022
West Virginia		-	-	2–20	2023

[a] Maryland Department of Transportation State Highway Administration specifies standards for soil salvaged from jobsites (S) and furnished topsoil (F).

experiment took place. Simulated rain events were equivalent to a 2.54 cm rainstorm (~8720 mL) and were applied to each tub at an approximate rate of 102 mm·hr^{-1}. Tap water was used due to the large scope of the project and the volume needed. Additionally, supplemental tap 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. The volume of the leachate collected in each bucket was measured after every SRE. Leachate samples were analyzed in the UMD Environmental Engineering Laboratory for Total N and Total P, in addition to other measured parameters described in Pamuru et al. (2024) (i.e., speciation and the associated concentrations of N and P forms). Additionally, a 1-L sample of tap water (influent "rainfall") was collected and analyzed for each SRE to account for N and P that were present.

2.3. Soil analyses

Aside from soil bulk density, which was only measured at the end of the experiment, individual samples were extracted twice from each replicate tub, before the first SRE and after the last. To determine bulk density, sampling rings were hammered into treatments to extract a known volume of soil. Soil was removed from the rings and dried at 105 °C for 24 h. The mass of dry samples was then divided by the volume of the rings (250 mL). All soil samples were tested by both the UMD Environmental Engineering Lab and Matrix Sciences, Chicago, Il (formerly AgroLab of Harrington, DE) for soil chemical properties, which included: electrical conductivity (EC), pH, cation exchange capacity (CEC), OM concentration (OM%), total nitrogen (TN), NO_3^--N, NH_4^+-N, C:N ratio, total phosphorus (TP), Mehlich-3 P (M3P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), manganese (Mn), iron (Fe), aluminum (Al), boron (B), copper (Cu), and sulfur (S). Test methods are identified in Table 2. The laboratory where specific analyses were conducted is identified in the results section.

2.4. Plant growth and nutrient uptake analyses

2.4.1. Analysis of percent coverage

Turfgrass coverage was quantified over time, using digital image analysis (Richardson et al., 2001). 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 4240 × 2832, which created a 12-megapixel digital image. A camera box (48.25 cm × 69.58 cm × 43.81 cm) was constructed out of plywood to block interference from outside light. A hole (9 cm) was cut on the top to mount the camera at a fixed height above the substrate surface (40 cm). The camera was held in place with a ring of foam (2.5 cm thick) to prevent light leakage and camera movement. Two 160 lm 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 6000 K color white light. Photos were analyzed for percent coverage using software (Turf Analyzer, Green Research Services, LLC).

Table 2
Summary of soil test methods used for the greenhouse microcosm study.

Analysis	Method summary	Method reference
OM content (OM%)	Loss on Ignition (LOI)	(Schulte and Hoskins, 2011)
pH	1:1 (soil:water)	(Eckert and Sims, 2011)
Soluble salts	EC; 1:2 (soil:water)	(Gartley, 2011)
Cation exchange capacity (CEC)	Summation	(Ross and Ketterings, 2011)
Total P (TP) and Cu	Acid digestion, followed by Inductively coupled plasma spectroscopy (ICP) analysis	("Method 3050B,", 1996)
Total nitrogen (TN) Total carbon (TC)	Combustion	(Bremner, 1996) (Nelson and Sommers, 1996)
Ammonium-N (NH_4-N)	KCl extraction, followed by diffusion-conductivity	(Gaviak et al., 2003)
Nitrate-N (NO_3-N)	KCl extraction, followed by the Cd Reduction Method	(Griffin et al., 2011)
Extractable P (M3P), K, Ca, Mg, Mn, Cu, Na, B, S, Fe, and Al	Mehlich 3 extraction followed by ICP analysis	(Mehlich, 1984) (U.S. EPA Method 6010C, 2000)

2.4.2. Height and dry mass measurements

Vegetation was harvested 8 weeks after seeding. Before harvesting turfgrass shoots, the height of 10 randomly selected primary shoots per tub were measured with a ruler from the base of the crown to the tip. Then, turfgrass shoot biomass was cut at the soil surface. Once harvested, shoots were immediately refrigerated until all microcosms were processed. Fresh mass samples were sent overnight to Matrix Sciences for next day tissue analysis. After drying, biomass was recorded by Matrix Sciences. To quantify root dry mass, a representative (10.16 cm diameter) soil core was taken from each tub by gently hammering a metal cylinder through the microcosm 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. The remaining roots were placed in paper bags and dried at 50 °C for 48 h.

2.4.3. Tissue analysis

Turfgrass clippings were sent to Matrix Sciences for analysis of % N, % P, % K, % Ca, % Mg, % S, % Na, Zn (ppm), Fe (ppm), Mn (ppm), Cu (ppm), B (ppm), and Mo (ppm). Nitrogen was assessed via combustion (Horneck and Miller, 2019) and the remaining nutrients were assessed using Inductively Coupled Plasma (ICP) spectroscopy after plant tissue was digested (Huang and Schulte, 1985).

2.5. Nutrient recovery calculations

Soil, tissue, and leachate TN and TP were recorded for each replicate microcosm. As a result, assessments of soil N and P gains and losses were compared to losses associated with leaching and plant uptake to provide a general picture of the state of soil fertility after turfgrass establishment and nine SREs. These calculations help discern whether N and P additions were adequate or in excess for turfgrass establishment. They do not reflect complete mass balances because atmospheric N losses (either through volatilization or denitrification) were not measured. Estimates for initial and final soil N and P were determined by multiplying soil concentrations by the estimated dry mass of soil in each tub. Cumulative leachate totals were determined by adding the weekly product of leachate volume multiplied by the corresponding concentration of N or P for each microcosm replicate. The cumulative application of N and P via SRE tap water was calculated by adding the products of the respective weekly concentrations multiplied by the volume of simulated stormwater applied each week (8720 mL). Plant uptake was determined by multiplying respective tissue concentrations by the total dry shoot mass.

2.6. Statistical analyses

Statistical analyses were performed using SPSS version 29 (IBM Corp., Armonk, NY). Homogeneity of variance was determined using Lavene's test. Where indicated, a one-way analysis of variance (ANOVA) was performed to compare treatment effect on soil nutrient concentrations, growth measurements, and tissue nutrient concentrations. When ANOVA revealed a statistically significant difference between at least two groups ($F(3,12) > 3.49$, $p < 0.05$ – except where indicated), a post-hoc test was performed using either the Bonferroni correction for equal variances, or the Games-Howell method for unequal variance, to determine if pairwise comparisons were significant. Pairwise *t*-tests were performed on select before/after soil measurements to determine if nutrient concentrations were statistically different. When statistical differences are presented, treatment means, standard errors (SE), and *p*-values are listed within the text or the specified table/figure.

3. Results and discussion

3.1. Amendment effects on soil OM, pH, and SS contents

As intended, the initial OM concentrations of MAT, LAT, and BAT were higher than CUT (Table 3); however, the results demonstrate the difficulty in constructing a predetermined OM concentration in amended soils. This is because calculating the amount of OM supplied depends on bulk density, % dry matter, and % organic matter (Sullivan et al., 2018). The concentration of dry matter is dependent on water content, which is subject to change depending on climatic conditions. Therefore, the OM concentration of the amendment on the day of incorporation may not reflect the OM concentration on the day the amendment was sampled. Additionally, the bulk density of an amendment within a given volume will depend on how much the amendment settles when it is loaded. Even though bulk density can be easily controlled in a laboratory setting, it is hard to control in the field where incorporation rates are commonly based on volume (e.g., cubic yard), not mass.

Biosolids incorporation had the greatest effect on soil pH and EC (Table 3). The initial and final pH measurements for BAT, 6.79 ± 0.02 and 7.21 ± 0.03, were lower than the other treatments, and were within the pH ranges specified by all Mid-Atlantic DOTs (4.1–7.6), except Virginia (where the maximum is 7.0). While the initial results for CUT, MAT, and LAT were within most DOT ranges, results were slightly higher (>7.5) after leaching and turfgrass establishment. Shifts in pH were consistent with previous research. Enrichment of soil with organic matter, such as compost, is known to raise pH (Angelova et al., 2013). However, some biosolids products have the opposite effect following incorporation (McIvor et al., 2012; Dede et al., 2017). In this case, soil acidification in the BAT treatment was likely caused by nitrification (Pierre, 1928) since biosolids significantly raised the concentration of NH_4^+ (discussed below).

Table 3
Tub Study initial (I) and final (F) soil fertility summary. Treatments included an unamended topsoil (CUT) and a soil amended with either finely shredded tree mulch (MAT), composted yard waste (LAT), or biosolids (BAT). Analyses are expressed as mean ± the standard error. Sufficiency (Suf.) ranges for OM, pH, EC are based on MDOT SHA Standard Specifications for Construction and Materials 920.01.02. Macronutrient ranges are based on general turfgrass recommendations and Mehlich 3 extractions (Carrow et al., 2001). Values that fall outside of recommended ranges are annotated with **boldface type**. Where a *p*-value is listed, ANOVA was performed to determine if significant differences existed among treatments. Values in rows with different letters are significantly different (α = 0.05). Results for nutrients are reported in mg·kg^{-1}.

Analysis*	Suf. Range	Time	CUT	MAT	LAT	BAT	*P* Value
OM%*	4-8	I	4.34 ± 0.1	6.86 ± 0.2	5.92 ± 0.2	5.64 ± 0.0	
		F	3.99 ± 0.1	5.41 ± 0.1	5.06 ± 0.1	5.1 ± 0.2	
pH*	6.1–7.4	I	7.21 ± 0.01	7.31 ± 0.01	7.18 ± 0.02	6.79 ± 0.02	
		F	**7.55 ± 0.02**	**7.52 ± 0.01**	**7.55 ± 0.01**	7.21 ± 0.03	
EC*mmhos/cm	≤ 0.78	I	0.30 ± 0.01	0.28 ± 0.03	0.59 ± 0.03	**1.89 ± 0.03**	
		F	0.28 ± 0.01	0.37 ± 0.02	0.34 ± 0.00	0.57 ± 0.051	
CEC meq/100 g		I	13.3 ± 0.3	15 ± 0.4	18.1 ± 0.4	15.5 ± 1.1	
		F	11.2 ± 0.7	12.4 ± 0.3	12.7 ± 0.3	13.7 ± 0.7	
C*		I	15,522 ± 321	29,631 ± 956	25,901 ± 490	22,868 ± 620	
		F	15,923 ± 211	25,360 ± 975	22,414 ± 834	23,799 ± 1040	
Total N*		I	1386 ± 12^{a}	1460 ± 35^{ab}	2223 ± 125^{b}	2934 ± 46^{c}	<0.001†
		F	1394 ± 58^{a}	1664 ± 74^{b}	1908 ± 58^{b}	2553 ± 109^{c}	<0.001†
C:N*		I	11:1	20:1	12:1	8:1	
		F	11:1	15:1	12:1	9:1	
NO_3-N		I	35 ± 2.5^{a}	28 ± 3^{a}	81 ± 6^{b}	136 ± 17^{c}	<0.001
		F	0.6 ± 0.1	0.9 ± 0.5	0.3 ± 0.3	8.4 ± 4.4	0.068
NH_4-N		I	1.2 ± 0.4^{a}	0.9 ± 0.3^{a}	0.9 ± 0.4^{a}	88.0 ± 3.5^{b}	<0.001
		F	2.4 ± 0.3	2.2 ± 0.4	1.9 ± 0.3	3.0 ± 0.5	0.29
Total P		I	530 ± 20^{a}	537 ± 17^{a}	599 ± 30^{a}	1394 ± 78^{b}	<0.001
		F	506 ± 22^{a}	500 ± 4^{a}	570 ± 17^{a}	1357 ± 148^{b}	<0.001
M3P	27–55	I	**15 ± 0.4^{a}**	**15 ± 0.3^{a}**	40 ± 0.6^{b}	37 ± 3.7^{b}	<0.001†
		F	**14 ± 1.0^{a}**	**13 ± 0.5^{a}**	**22 ± 0.3^{a}**	42 ± 7.4^{b}	<0.001†
K	50–116	I	**127 ± 1.7^{a}**	**144 ± 0.3^{a}**	**286 ± 10.0^{c}**	**162 ± 6.0^{b}**	<0.001
		F	**104 ± 2.2^{a}**	**122 ± 2.9^{b}**	**176 ± 1.8^{c}**	85 ± 6.0^{a}	<0.001
Ca	375–750	I	**2329 ± 59^{a}**	**2621 ± 77^{ab}**	**3026 ± 73^{b}**	**2690 ± 213^{ab}**	0.014
		F	**1950 ± 64**	**2150 ± 64**	**2150 ± 50**	**2400 ± 147**	
Mg		I	126 ± 3^{a}	147 ± 3^{b}	213 ± 3^{c}	142 ± 5^{b}	<0.001
		F	111 ± 2	130 ± 3	152 ± 2	134 ± 4	
Mn		I	260 ± 4^{b}	255 ± 15^{b}	260 ± 4^{b}	230 ± 4^{a}	<0.001
		F	220 ± 6	208 ± 2	193 ± 2	177 ± 6	
Fe		I	313 ± 5^{a}	355 ± 10^{bc}	340 ± 12^{ab}	383 ± 8^{c}	<0.001
		F	243 ± 3	264 ± 2	239 ± 3	301 ± 16	
Al		I	760 ± 8	763 ± 5	760 ± 9	730 ± 12	0.075
		F	658 ± 10	627 ± 4	605 ± 6	649 ± 17	
Cu		I	3.1 ± 0.1^{a}	3.1 ± 0.1^{a}	3.2 ± 0.1^{a}	4.00 ± 02^{b}	<0.001
		F	2.6 ± 0.1	2.5 ± 0.0	2.7 ± 0.1	4.9 ± 0.0	
B		I	0.8 ± 0.01^{a}	1.0 ± 0.01^{b}	1.3 ± 0.02^{c}	1.00 ± 0.48^{b}	<0.001
		F	0.6 ± 0.01	0.7 ± 0.01	0.9 ± 0.00	0.7 ± 0.01	
SO_4^{2}-S	15–40	I	40 ± 2^{a}	34 ± 1^{a}	**41 ± 1^{a}**	**149 ± 17^{b}**	<0.001
		F	17 ± 3	**10 ± 1**	**12 ± 1**	**59 ± 23**	
Na		I	20 ± 1^{a}	21 ± 1^{a}	28 ± 1^{b}	24 ± 1^{ab}	<0.001
		F	28 ± 2	28 ± 0	30 ± 1	30 ± 2	

* Analyses performed by the UMD Environmental Engineering Lab. Others were performed by Matrix Sciences.

† The Games-Howell post hoc test was used for pairwise comparisons due to unequal sample sizes and/or variance. Otherwise, the Bonferroni test was used.

Considering EC, the initial BAT mean result (1.89 ± 0.03 mmhos/cm) was higher than all other results and was above the maximum limit specified by MDOT (1.25 mmhos/cm), which has the least restrictive SS restriction for the two Mid-Atlantic agencies that impose a limit. (Note: The 6 remaining agencies do not have a SS limit). After leaching and establishment, BAT EC was 0.57 mmhos/cm — still higher than the results for the other treatments. Even so, growth measurements (discussed below) from turfgrass grown in BAT showed that biosolids enhanced growth.

The appropriateness of some Mid-Atlantic DOT pH and SS standards, intended for areas stabilized with turfgrass, do not align with published research. For example, the highest pH observed, 7.55, was unlikely to restrict turfgrass seedling growth and subsequent establishment. Zhang et al. (2012) found no decline in Kentucky bluegrass quality at a mild (8.0) alkali stress. Furthermore, the grass species used in this study (common cool season species) are tolerant of soil pH < 6.0 (Carrow et al., 2001). In regards to soluble salts, Harivandi et al. (1992) reported general difficulty in establishment and maintenance of turfgrass cultivars when EC exceeded 3 mmhos/cm for Kentucky bluegrass and 6 mmhos/cm for tall fescue. These ranges far exceed MDOT SHA's current limit of 1.25 mmhos/cm. Based on this evidence, it is unlikely that salts restricted growth in the three treatments that exceed the MDOT SHA soluble salt standard. Therefore, available research coupled with the growth results discussed below support a maximum SS standard higher than 1.25 mmhos/cm and a more expanded pH range than several Mid-Atlantic DOTs specify for disturbed soils where tall fescue and/or Kentucky bluegrass will be planted.

3.2. Amendment effects on soil nutrients and bulk density

Soil test results (Table 3) show that composted yard waste and biosolids significantly increased the availability of plant macronutrients (N, P, and K). Specifically, LAT initially had twice as much NO_3^- than CUT while BAT had 4 times more. Additionally, BAT had significantly more NH_4^+ after amendments were incorporated than any other treatment. Combined, plant available nitrogen (PAN) in BAT was 6 times greater than in CUT. Only biosolids significantly increased soil TP. Initial and final BAT TP concentrations were >2 times greater than in all other treatments. Mehlich 3-P (M3P) is widely used as an agronomic soil test for P (Sims et al., 2002) and measures how amendments affected P availability. Results showed that LAT and BAT had significantly more MP3 than CUT and MAT, which were deficient. However, the increase in LAT was not sustained after growth and leaching, while it was sustained in BAT. Composted yard waste and biosolids also significantly raised the initial K concentration of LAT and BAT above the concentration for CUT; but only LAT sustained a higher K concentration after growth and leaching. Notably, neither PAN, M3P, or K was greater in MAT than CUT. Furthermore, results suggest that the mulch amendment likely removed PAN based on the C:N ratios of CUT and MAT, which were 11:1 and 20:1, respectively.

Another notable difference in soil fertility is highlighted by the results for sulfate (SO_4^{2}-S). Sulfur, a plant secondary-macro nutrient, is taken up as SO_4^{2-}. Since SO_4^{2-} can be leached out of soil, it must be replaced by S-containing sources. Reductions in atmospheric deposition of S and S-containing fertilizers and fungicides, have resulted in more frequent cases of S deficiencies in soils throughout the world (Wainwright, 1984). Amending the control soil with mulch and composted yard waste did not significantly alter the initial SO_4^{2}-S concentration of CUT, which was near the upper limit of the recommended sufficiency range of 40 $mg \cdot kg^{-1}$ (Carrow et al., 2001). On the other hand, biosolids raised the SO_4^{2-} concentration to 149 $mg \cdot kg^{-1}$; it remained above the sufficiency range after growth and leaching while the other treatments fell below range.

Although not the focus of this manuscript, amendment effects to soil physical properties were noted. For example, mean bulk densities were 1.21 ± 0.03, 1.4 ± 0.04, 1.21 ± 0.04, and 1.21 ± 0.07 $g \cdot cm^{-3}$ for CUT, MAT, LAT and BAT, respectively. The density of MAT was significantly higher than CUT ($F(3,8) = 8.73$, $p = 0.007$). This result indicates that finely shredded wood mulch may negatively impact the infiltration rate of amended soil since the infiltration capacity of soils decreases with increasing soil bulk density (Li et al., 2009). However, densities across treatments were ideal for sandy and silt loams and likely would not have restricted root growth ("Bulk Density," 2008). Additional treatment effects on soil physical properties such as particle size distribution, compaction, direct shear, and saturated hydraulic conductivity are discussed in Pamuru et al. (2024).

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 (Petrovic et al., 2005). Therefore, the soil fertility concerns summarized above are discussed in relation to the plant tissue analyses and growth measurements in the following sections.

3.3. Amendment effects on turfgrass growth measurements and percent coverage

Turfgrass establishment and growth in MAT was poor as compared to the other treatments. For example, CUT, LAT, and BAT achieved over 60 % coverage by week 4 (Fig. 1). Two weeks later, mean turfgrass coverage was ≥90 % for the control treatment and ≥ 95 % in LAT and BAT replicates. On the other hand, mean coverage for MAT was significantly lower than all other treatment averages and never exceeded 33 % coverage.

In addition to coverage, amendment effects were noted in turfgrass height and shoot dry mass (SDM). Mean height for MAT turfgrass was only 10.8 ± 0.7 cm, at least 50 % less than all other treatments (Table 4). While turfgrass height was similar between CUT and LAT, it was significantly greater in BAT, compared to CUT. Mean SDM was different across all treatments such that MAT < CUT < LAT < BAT (Table 4). These results are helpful in demonstrating that although turfgrass coverage was similar in LAT and BAT, significantly more above-ground growth occurred in BAT. This implies that amending topsoil with biosolids at a 10 % rate could result in more frequent mowing, at least initially.

Differences in shoot growth and coverage are predominately attributed to differences in N availability as determined by the C:N ratio. The median C:N ratio is typically 12:1 for an Ap horizon (Weil and Brady, 2017). The ratios for CUT, LAT, and BAT were below this benchmark but the ratio for MAT was 20:1. Although the C:N ratio of the amendments was not analyzed in this study, others provide benchmarks for landscape managers to consider when using organic amendments. Cogger (2005) reviewed soil studies in which compost was used to remediate disturbed urban sites and concluded that composts with a C:N ratio of 20:1 or less provided a ready supply of PAN. When such ratios were met, turf establishment was improved and the amount of supplemental nutrients applied was reduced. On the other hand, Schmid et al. (2017) conducted a turf-compost study in which the compost C:N ratio was 41:1. Establishment was initially delayed; however, the amended soil sustained greater turf quality compared to the unamended plots after the effect of the imbalance wore off. Together, these studies demonstrate the importance of balancing the C:N ratio of amendments with short- and long-term goals as well as the need to provide supplemental N when the ratio is high to facilitate turfgrass establishment.

The amended treatments also affected root growth, with implications for infiltration rates and enhanced soil stabilization. The root dry mass (RDM) of MAT was statistically lower than CUT and LAT, whereas BAT was similar to all (Table 4). Huang et al. (2017) demonstrated that below-ground biomass positively correlated with the soil infiltration rate in grasslands. Furthermore, the study concluded that below-ground biomass was the most important factor affecting infiltration when compared to total porosity, capillary porosity, soil organic matter and

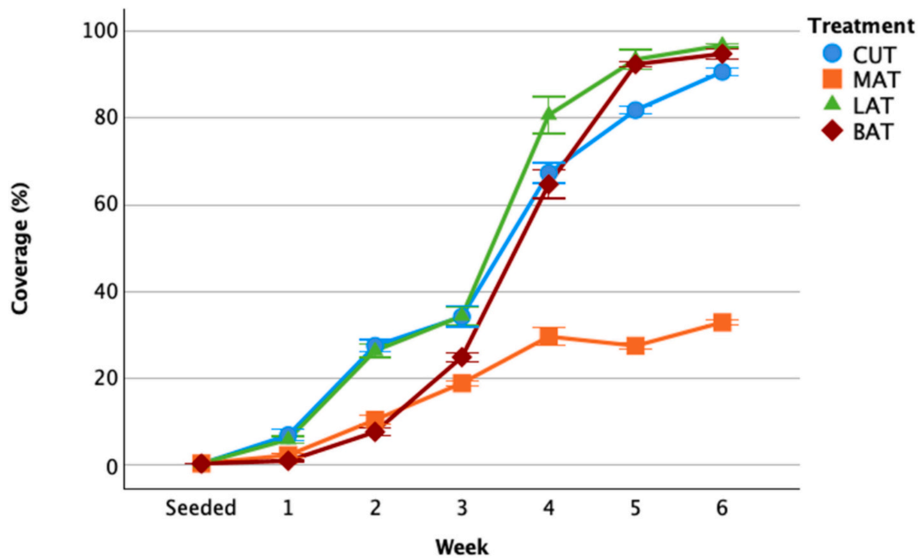

Fig. 1. Turfgrass percent coverage as determined by digital analysis. Microcosms were seeded on 9/13/21. Error bars represent +/− the standard error.

Table 4
Vegetation growth measurements for turfgrass grown in manufactured topsoils. The treatments included an unamended control soil (CUT), a mulch amended soil (MAT), a leaf/yard waste compost amended soil (LAT), and a biosolids amended soil (BAT). Results are expressed as mean ± the standard error. ANOVA was performed to determine if significant differences existed between treatments. Values within rows which have different letters are significantly different from each other (α = 0.05).

	CUT	MAT	LAT	BAT	P-Value
Final % Cover	90.7 ± 0.9b	32.8 ± 0.6a	96.9 ± 0.4c	94.9 ± 1.2bc	<0.001
Height (cm)	20.7 ± 0.4b	10.8 ± 0.7a	26.6 ± 1.9bc	31.6 ± 0.9c	<0.001
Shoot Dry Mass (g)	24.0 ± 1.8b	7.5 ± 1.0a	39.4 ± 1.6c	67.7 ± 3.7d	<0.001
Root Dry Mass (g)[a]	0.94 ± 0.03b	0.33 ± 0.06a	0.85 ± 0.12b	0.58 ± 0.09ab	0.002
Root-Shoot Ratio	1.45 ± 0.18b	1.55 ± 0.18b	0.79 ± 0.14a	0.30 ± 0.03a	<0.001

[a] Soil cores were taken to determine root dry mass and are reported in this table. The volume of the core was scaled up to estimate the total mass of roots in each tub for root: shoot ratios.

soil aggregate. When evaluating root: shoot ratios (R:S), LAT and BAT were lower than CUT and MAT. Root: shoot ratio differences can be rationalized by the PAN results, where BAT and LAT > MAT and CUT. Turfgrasses respond to high NO_3^- levels by diverting carbohydrates to amino acid production instead of storage (in the form of sugars) in roots (Carrow et al., 2001), resulting in an emphasis on shoot growth instead of root growth. This explains why root dry mass in the BAT treatment was low and shoot growth was high. Root growth is important for stabilizing soil after construction activities to prevent erosion. Additionally, well-established root systems protect against drought and other environmental stresses (Brown et al., 2010). Therefore, applications of amendments that exceed N requirements for turfgrass should be avoided, to encourage healthy root development.

3.4. Plant tissue analysis

Tissue samples taken from CUT shoots were deficient in N, P, S, Cu, Zn, and B (Table 5). The same nutrient deficiencies were observed in LAT tissue even though composted leaf and yard waste increased the soil concentration of many nutrients. With the exception of Zn, tissue from the MAT treatment exhibited the same deficiencies observed in CUT tissue, plus a K deficiency. Petrovic et al. (2005) concluded that tissue K

Table 5
Summary of turfgrass tissue nutrient concentrations. Results that fall below sufficiency (suf.) ranges for *Festuca arundinacea* (Mills and Jones, 1996) are annotated with boldface type. Results are expressed as mean ± the standard error. ANOVA was performed to determine if significant differences existed between treatments. Values in rows which have different letters are significantly different (α = 0.05).

Nutrient	Suf. Range	Control	Mulch	Leaf	Biosolids	P Value[*]
N (%)	3.4–4.65	**1.47 ± 0.06a**	**1.29 ± 0.03a**	**1.92 ± 0.18a**	4.51 ± 0.11b	<0.001
P (%)	0.34–0.50	**0.12 ± 0.00a**	**0.15 ± 0.00b**	**0.15 ± 0.01ab**	**0.24 ± 0.01c**	<0.001
K (%)	3.00–4.00	3.18 ± 0.10	**2.79 ± 0.10**	4.03 ± 0.22	4.51 ± 0.10	NA
Ca (%)	0.40–0.45	0.82 ± 0.05	1.00 ± 0.06	0.85 ± 0.17	1.09 ± 0.12	NA
Mg (%)	0.24–0.29	0.37 ± 0.01	0.39 ± 0.01	0.39 ± 0.01	0.48 ± 0.01	NA
S (%)	0.40–0.44	**0.16 ± 0.00ab**	**0.15 ± 0.00a**	**0.20 ± 0.01b**	**0.28 ± 0.00c**	<0.001
Fe ($mg \cdot kg^{-1}$)	83–167	280 ± 63	389 ± 64	207 ± 20	241 ± 22	NA
Mn ($mg \cdot kg^{-1}$)	54–74	73 ± 4	106 ± 5	65 ± 6	71 ± 3	NA
Cu ($mg \cdot kg^{-1}$)	9–15	**6 ± 0a**	**6 ± 0a**	**7 ± 1a**	13 ± 0b	<0.001
Zn ($mg \cdot kg^{-1}$)	28–64	**20 ± 0a**	30 ± 1b	**26 ± 2ab**	41 ± 1c	<0.001
B ($mg \cdot kg^{-1}$)	15–20	**5.0 ± 0.4ab**	**6.0 ± 0.0b**	**4.8 ± 0.2a**	**4.3 ± 0.2a**	0.004

[*] Statistical differences were not investigated unless a nutrient deficiency was noted.

content is positively correlated with N application. Therefore, the K deficiency observed in MAT shoots is explained by PAN, which was lowest in MAT. Overall, biosolids provided the best general fertilizer value, especially in terms of N, and resulted in the least number of tissue deficiencies (i.e., P, S, and B). Each treatment resulted in a B deficiency that is explained by heavy leaching, which was induced by the SREs (Xu et al., 2001). Tissue P and S deficiencies in the BAT treatment are harder to explain considering the degree to which biosolids increased soil P and SO_4^{2-} concentrations.

When P is bound to Fe, Al, and Ca as inorganic phosphates, it is not plant available (O'Connor et al., 2004). The wastewater treatment plant that produced Fresh Bloom®, the biosolids used in BAT, reported use of iron salts (ferrous sulfate), liquid alum, and lime during the wastewater treatment process ("Blue Plains NPDES Factsheet,", 2017). The initial soil test results showed that the Fe concentration of BAT was higher than the control, suggesting that Fe was used to remove P from wastewater. These findings explain why a tissue P deficiency was identified in BAT replicates despite sufficient initial M3P concentrations. Similar results were reported by O'Connor et al. (2004) and Boen and Haraldsen (2011).

In regards to S, tissue concentrations were below the recommended range for tall fescue, 0.40 % - 0.44 % (Mills and Jones, 1996), and ranged from 0.15 % ± 0.00 for MAT to 0.28 % ± 0.00 for BAT. Despite the low concentration of S in BAT tissue, the results show that biosolids were a source of plant available S. Scherer (2009) theorized that organic-S contributes to the S supply of plants, especially in deficient soils, because biochemical mineralization is controlled by S supply, which is dominated by organic S (typically >95 % of total soil S). Biederbeck (1978) explained that total soil S is significantly correlated with soil organic C and TN, which were all significantly higher in BAT than the control. However, high soil-nitrates can impede plant-uptake of SO_4^{2-} (Mills and Jones, 1996). Keeping in mind that the tub study was short in duration (9 weeks from the first SRE to harvest), these results along with similar results (Shearin, 1999; Moore, 2022) suggest that biosolids could be a long-term source of plant available S, but uptake may be impeded until the release of NO_3^- from the biosolids is reduced.

The most notable tissue nutrient difference was related to N, which was statistically highest for the BAT treatment at 4.51 % and considered sufficient for tall fescue (Mills and Jones, 1996). Otherwise, N deficiencies were observed in the tissue of all other treatments, which ranged between 1.29 % and 1.92 % (Table 5). High concentrations of PAN (NO_3^- and NH_4^+), in BAT explain the difference. Altogether, soil and tissue test results demonstrate that (aerobically digested) biosolids can be used as a general fertilizer, supplying PAN, MP3, S, and other plant nutrients.

3.5. Uptake and loss comparisons of nitrogen and phosphorus

The amount of N and P taken up by turfgrass shoot mass was determined by multiplying the tissue concentrations by the corresponding dry mass value. Normalization of tissue contents is important as growth differences significantly affect elemental tissue concentrations, which can confound results (Lea-Cox et al., 2001; Ristvey et al., 2007). Shoot growth, and subsequent N uptake, in the BAT treatment exceeded others (Table 6). This is best explained by the concentrations of PAN which were the highest in BAT, while the average C:N ratio was the lowest. The combination of these factors likely allowed for N mineralization as the experiment progressed, thereby replacing N that was taken up by turfgrass, lost to the atmosphere, and/or leached. Consequently, mean N uptake was >4 times higher in BAT as compared to other treatments. On the other hand, the plant tissue results indicate that soil N availability was insufficient and likely limited the growth of the other three treatments. This is especially true for MAT, as evident by the shoot dry mass results discussed earlier.

Similar to the N results, mean shoot P uptake (Table 7) was significantly greater in BAT than all other treatments. This can be explained by the higher concentration of M3P sustained in BAT, which is evident by the final soil test results discussed earlier (Table 3). Even so, the tissue analysis indicated that BAT turfgrass was deficient in P, suggesting that had more of the TP in BAT been phytoavailable, P uptake would likely have been greater.

As with the N and P tissue uptake calculations, normalized leachate N and P content (Pamuru et al., 2024) was calculated (volume × concentration) so that uptake could be compared to leachate losses (Tables 6 and 7, respectively). The average monthly cumulative rainfall for the months roughly coinciding with the study timeframe (Sept and Oct, 2021) in Prince George's County, MD (where the study took place), is 170 mm. This is slightly less than the cumulative amount applied over each SRE, 203 mm ("Normal Precipitation by Month,", 2023). Approximately 1.1 mg-N·L^{-1} was present in the tap water used for the experiment; the total applied was approximately 82 mg. Any other N addition would have come from N fixation, which combined with low growth rates could explain why the final MAT soil N concentration was higher than the initial concentration by approximately 10.7 g. Overall, the results show that more N (26 % - 47 %) was removed from the soil through leaching than was assimilated into plant biomass for each treatment, including CUT.

The pattern of N uptake and leaching was reflective of TN soil contents and N availability (Table 6), which was highest from BAT > LAT > CUT > MAT. Even though MAT had a statistically similar concentration of soil TN as CUT, less N was leached and assimilated, which can be explained by N immobilization caused by the high C:N ratio of MAT. The addition of biosolids resulted in 10 times more N leaching from BAT than CUT (Pamuru et al., 2024). The next highest loss came from LAT, which was 1.7 times greater than CUT. The difference between N uptake and leaching was greatest from BAT (2.7 g), lowest from MAT (0.07 g) and similar for CUT and LAT (0.24 g and 0.27 g, respectively). Ideally, the amount taken up is greater than the amount leached to reduce waterborne N pollution, but this is difficult to achieve. These results considered alongside growth measurements suggest that the amount of biosolids used in this experiment to raise the soil OM content approximately 2 % (by mass) was far in excess of plant N requirements, and could result in significant N leaching if biosolids amendments were applied to disturbed soil at this rate.

For each treatment, mean soil TP was statistically similar at the beginning and end of the experiment. This was reflected by minimal leaching and uptake losses (Table 7). In each case, P uptake was greater than P leached. The ratios for uptake:leached were approximately 4:1,

Table 6
Soil N (g) before and after 228.6 cm of simulated rainfall were applied to microcosms, which included a control soil (CUT) and soil amended with either finely shredded wood mulch (MAT), composted leaf yard waste (LAT) or biosolids (BAT). Turfgrass biomass was analyzed to determine total N uptake, which is listed next to the cumulative of N content leached. Results are reported as means ± the standard difference. Leachate data from Pamuru et al. (2024).

Treatment	Soil N Start (g)	Soil N End (g)	Soil Difference (g)	N Leached (g)	Shoot N Uptake (g)
CUT	64.50 ± 0.95	64.90 ± 6.26	−0.40	0.60 ± 0.09	0.36 ± 0.08
MAT	76.80 ± 3.18	87.50 ± 10.04	−10.7	0.17 ± 0.02	0.10 ± 0.03
LAT	103.10 ± 10.21	89.10 ± 8.70	14.00	1.03 ± 0.09	0.76 ± 0.19
BAT	136.60 ± 3.40	118.90 ± 13.64	17.80	5.76 ± 0.22	3.06 ± 0.47

Note: Approximately 0.082 g of N was applied during simulate rain events since N was present in the water used for the experiment.

Table 7
Soil phosphorus (g) before and after 228.6 mm of simulated rainfall was applied to microcosms. Treatments included a control soil (CUT) and soil amended with either finely shredded wood mulch (MAT), composted leaf yard waste (LAT) or biosolids (BAT). Soil before and after results were not significantly different as reflected by the associated test statistics and *p*-values (α = 0.05). Turfgrass biomass was analyzed to determine total P uptake (mg), which is listed next to the cumulative P content leached (mg). Results are reported as means ± standard error. ANOVA was performed on the leachate and uptake results to determine if significant mean differences existed between treatments. Values in columns with different letters are significantly different (α = 0.05; $p < 0.001$). Leachate data from Pamuru et al. (2024).

Treatment	Soil P Before (g)	Soil P After (g)	Soil Difference (g)	Soil t-test *p*-value	P Leached (mg)	Shoot P Uptake (mg)
CUT	24.67 ± 0.90	23.61 ± 1.00	1.06 ± 0.90	0.325	7.74 ± 0.48b	28.77 ± 2.05ab
MAT	28.22 ± 0.90	26.34 ± 0.22	1.88 + 0.80	0.104	4.34 ± 0.24a	10.98 ± 1.41a
LAT	28.36 ± 1.80	26.48 ± 0.80	1.87 ± 2.20	0.479	6.78 ± 0.40b	58.27 ± 4.32b
BAT	64.90 ± 3.60	63.18 ± 6.90	1.72 ± 9.60	0.869	5.16 ± 0.11a	161.90 ± 17.02c

Note: Approximately 0.026 g of P was applied during simulate rain events since P was present in the water used for the experiment.

2:1, 9:1, and 31:1 for CUT, MAT, LAT, and BAT, which demonstrates a higher plant uptake efficiency of mobile P in the LAT and BAT treatments as compared to CUT. Furthermore, CUT leached approximately the same mass as LAT and more than MAT and BAT, meaning the addition of the organic amendments did not increase P loading to leachate. Therefore the amendments used in this study to raise the concentration of OM by approximately 2 % (by mass) in the base soil used for this study would likely not result in excessive P loading to groundwater from the first 200 mm of rainfall (Pamuru et al., 2024) even though LAT and BAT increased soluble P (MP3) in soil and BAT increased TP. Longer-term studies would be needed to monitor losses from biosolids since soil TP was raised so significantly and P mineralization over time, coupled with saturation of adsorption sites, could lead to P pollution in stormwater (Fiorellino et al., 2017).

4. Conclusions

This study highlights the challenge landscape managers may have ensuring wanted results when specifying a desired OM concentration to raise OM. Difficulty arises from scaling laboratory bulk density results to large scale landscaping projects, which rely on volume rather than mass to measure materials. Fluctuating water contents within amendments further complicate laboratory test results. Managers determined to ensure a minimum OM concentration should test amended soil before planting to allow for further adjustments to be made, if necessary.

Biosolids lowered soil pH after incorporation due to a large supply of mineralizable N and conditions conducive to nitrification. Biosolids also significantly raised the concentration of SS in amended soil, as determined by EC. Growth was not restricted as a result of soluble salt additions. After 203 mm of simulated rainfall, the EC of biosolids amended soil was reduced by 70 %. While Mid-Atlantic DOT topsoil standards for pH and SS are well within the ranges conducive for the establishment of common cool-season grasses (Kentucky bluegrass and tall fescue), some may be overly restrictive and preclude the use of organic amendments that raise SS or alter pH. Based on the results of this study, EC may be as high as 1.9 mmhos/cm; and soil pH may be as high as 7.55 without restricting Kentucky bluegrass and tall fescue growth. Research suggests that maximum limits could be expanded beyond these results, though additional studies are suggested before implementation of expanded standards, using the desired vegetative cover.

In addition to soil pH and SS content, landscape managers should consider C:N ratio, as well as macro- and micro-nutrient concentrations, to determine which organic amendment may be best for meeting turfgrass fertility requirements while minimizing nutrient pollution. This study demonstrated that composted leaf and yard waste increased the availability of N, P, and K in soil and maintained a good C:N ratio, resulting in enhanced biomass production. However, nutrient additions did not prevent tissue deficiencies since the same deficiencies were noted in CUT and LAT treatment results.

While an 8 % addition of mulch increased soil OM, the high C:N ratio of MAT (~20:1) restricted the availability of PAN through immobilization, resulting in reduced shoot growth and enhanced R:S ratio. Mulch should not be used as a source of P since it neither increased soil TP or M3P. It did, however, help to retain soil P as evident by the leachate mass loss total which was lower than the associated control loss (Pamuru et al., 2024). Although this experiment was short in duration, initial and final C:N results (20:1 and 15:1, respectively) demonstrate that nutrients held by mulch will mineralize — though likely not in time to aid initial vegetation establishment. Therefore, a supplemental source of NO_3^- and NH_4^+ will be needed in mulch amended soil to improve turfgrass establishment.

Biosolids were a significant source of plant nutrients, especially N, P, and S, which enhanced shoot growth at the expense of root growth. While shoot biomass was highest in BAT and could result in higher maintenance costs, percent coverage was comparable to the LAT treatment. Pamuru et al. (2024) showed that even though P was stable in BAT, N was not, which resulted in heavy mass leachate losses of N. Despite losses, the influx of nutrients provided by biosolids allowed mineralized N and P to replace what was removed from soil by uptake and leaching for the duration of the experiment. Tissue N and P concentrations were highest in the BAT treatment, indicating that biosolids improved the N and P uptake rate. However, the higher N uptake rate observed in the BAT treatment was offset by a high mass loss of N in leachate. Taken together, these results demonstrate that N was applied well above turfgrass needs. If nutrient concentrations are known, biosolids could make an excellent general fertilizer providing N, P, S, and the full range of micronutrients. However, based on this study, the use of anaerobically digested, thermally stabilized biosolids to raise the OM concentration (by mass) of furnished topsoil by 2 % or more is not advised.

5. Recommendations

- Landscape managers should determine if disturbed or manufactured soil received an organic amendment. Subsequent soil testing and site nutrient plans should be adjusted based on reported amendment feedstocks.
- Composted leaf and yard waste can be used to raise soil OM, N and P contents; and to enhance turfgrass biomass production.
- Wood mulch should not be incorporated into disturbed soil without a supplemental source of readily available N in areas where landscape plans include turfgrass establishment.
- Biosolids can be used to enhance the full spectrum of plant nutrients; however, amendments should be used at the N-agronomic rate for turfgrass establishment to avoid excess maintenance costs, poor root establishment, and unnecessary N leachate losses.

CRediT authorship contribution statement

Jennifer Morash: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Sai Thejaswini Pamuru:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **John D. Lea-Cox:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Andrew G. Ristvey:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Allen P. Davis:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Ahmet H. Aydilek:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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