ABSTRACT

Title of Dissertation: THE USE OF ORGANIC WASTE PRODUCTS AS SOIL AMENDMENTS FOR TURFGRASS ESTABLISHMENT: EFFECTS AND REGULATORY INFLUENCES

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The use of organic waste products as soil amendments in highly disturbed urban soil is poised to grow due to rising fertilizer costs, waste-management issues, and greater emphasis on creating sustainable circular economies. Despite the advantages of using waste products as organic amendments to enhance fertility, their incorrect use may result in short-term unintended consequences such as nutrient losses or the immobilization of plant-essential nutrients, which could diminish efforts to establish vegetation on disturbed soil. To avoid these consequences, transportation authorities – cited as the largest users of compost in some states – have implemented measures to improve product specifications. This research details the efforts of one such organization, the Maryland Department of Transportation State Highway Administration

(MDOT SHA), and the results of an initiative to increase the quality of manufactured topsoil and compost use through agency topsoil specifications. After determining which products were most likely to be incorporated into manufactured topsoil (finely shredded wood mulch and composted leaf yard waste), two greenhouse microcosm experiments were conducted to evaluate plant growth responses and the efficiency of nutrient uptake compared to leachate losses when those amendments were used in accordance with MDOT SHA specifications. Composted yard waste provided excellent results while wood mulch suppressed growth in the short-term studies. A biosolids treatment was included in the experiments due to widespread availability and growing interest. Biosolids improved soil fertility and plant growth. However, the difference between nitrogen (N) uptake and leachate mass losses required a second set of experiments, to quantify the effects of four biosolids amendments on plant growth, nutrient uptake, and leachate losses. Treatments were applied at the rate recommended by UMD for turfgrass establishment (2.54 cm, incorporated) and included fresh biosolids, biosolids that were stockpiled for two years, two blended products made from either the fresh or aged biosolids and fine wood mulch, an inorganic fertilizer, and a control. Aging and wood fines reduced N leaching losses but at the expense of N inputs to soil. The cumulative N leachate mass loss from the new biosolids treatment was 63 times greater than the cumulative fertilizer total. Aging did not reduce phosphorus (P) leaching losses but wood fines did by diluting the concentration of P in blends. However, biosolids mostly retained P in the soil and cumulative fertilizer losses were 2 times higher. Overall, growth measurements showed that biosolids enhanced growth during the first and second growing seasons. However, based on the results of this research, 2.54 cm of pure biosolids is not required to enhance turfgrass establishment. An application of 1.27 cm of pure biosolids or 2.54 cm of a

biosolid/wood fine blend should provide comparable enhanced turfgrass growth results while reducing overall nutrient leachate losses.

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by

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Dedication

To Craig. Thank you for keeping your promise.

∞

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Chapter 1: Introduction

1.1 Organic Wastes as Soil Amendments

The use of urban organic waste products incorporated in manufactured topsoils and added to highly disturbed native soils has received increased attention as governing agencies and local municipalities search for sustainable solutions for organic waste management problems (Wang et al., 2008). Urban organic wastes include, but are not limited to: food waste, residential yard waste, wood waste from land clearing activities and saw mills, and wastewater treatment residuals – known as sewage sludge or biosolids. Diversion of these products from deposition in landfills to land applications eases waste management costs and reduces environmental pollution associated with organic wastes, e.g. methane production, while promoting the circular economy (Chia et al., 2020). Land managers and owners stand to gain from these efforts since the conversion of organic wastes into soil amendments and fertilizers improves soil fertility, enhances vegetation establishment, and reduces erosion (Curtis and Claassen, 2009; Brown and Gorres, 2011; Donn et al., 2014).

Organic amendments increase the concentration of organic matter (OM) in soil. With increased OM comes a miscellany of enhancements to soil physical, biological, and chemical properties, such as bulk density, porosity, aeration, microbial count/activity, and the availability of macro- and micro-nutrients (Diacono and Montemurro, 2010). Nutrients are released directly into soil from weathered and/or decomposed material, or indirectly by microbes that feed on OM. Additionally, OM boosts cation exchange capacity (CEC), which helps to retain soil nutrients (Booze-Daniels et al., 2000; Jiang et al., 2018).

Nitrogen and P are essential to plants and animals. Even though these elements are abundant in nature, forms that are useful to life are limited. Once biological fixation has occurred, decomposition of organic matter is an important process for retaining plant available forms of N (NH_4^+ and NO_3^-) and P (orthophosphates: $H_2PO_4^-$ and HPO_4^{2-}) in soil. The conversion of organic N and P to inorganic forms is facilitated by soil microbes and is known as mineralization. Organically bound N is first transformed through mineralization to NH_4^+, followed by NO_3^-. Excess nitrogen is released into the soil solution once microbial needs have been met and is then available for plant uptake. This plant available nitrogen (PAN) is unstable in the soil solution and can be rapidly transformed by microbes into gaseous forms, predominately N^2 via denitrification. Additionally, PAN as NO_3^- is suspectable to leaching due to its negative charge, which does not bind to negatively charged soil particles.

Generally speaking, mineralized P is more stable in soil. This is because P is not converted into gaseous forms by soil microbes. Additionally, soluble P (i.e. orthophosphates) can attach to cations such as iron, aluminum and calcium, depending on the pH and their availability. Therefore, soluble P is stripped from solution as water travels through the soil matrix. The exception is when soil phosphorus levels are very high and sorption sites are full. Under this scenario, P is more suspectable to leaching (Heckrath et al., 1995). Even so, particulate-bound P is the primary pathway for P losses from soil. This is especially true in coarse/sandy soils where water percolates more readily (Glæsner et al., 2011).

Products that are fully composted generally release nutrients slowly over time, stretching plant benefits over multiple seasons (Sullivan et al., 1998). If the carbon to nitrogen ratio (C:N) is above 25:1, products may temporarily immobilize soil nitrogen (N), often resulting in growth restrictions until the essential nutrient is cycled back into plant available forms, i.e. nitrate (NO_3^-) and ammonium (NH_4^+) (Jansson and Persson, 1982; Cogger, 2005). On the other hand, biosolids, which may or may not be composted, often provide soluble nutrients, especially NO_3^- and NH_4^+, immediately following incorporation (Rigby et al., 2016). Table 1.1 summarizes average N and phosphorus (P) concentrations of various organic amendments gathered by Lee (2016) and Wierzbowska et al. (2020). Understanding nutrient differences, coupled with proper selection of OM amendments to affect short- and long-term nutrient needs, can help users improve the growth and performance of vegetation and reduce fertilizer needs and maintenance costs.

Table 1.1: Reported Total Nitrogen and Total Phosphorus averages for various organic amendments. Information summarized from Cogger et al. (2004); Lee (2016); and Wierzbowska et al. (2020).

Amendments	Total N (g kg^{-1})	Total P (g kg^{-1})
Composted Biosolids	11.77	8.03
Anaerobically digested biosolids	46	-
Manure Wastes	30.4	14.3
Composted Municipal Wastes	6.94	2.94
Composted Green (yard) Wastes	4.05	3.23
Industrial Organic Waste	16.3	8.6

Aside from biosolids, which may require a federal permit for land application (depending on the quality of the product), there are few direct restrictions that apply to organic waste products that are used in urban soil. This is not the case for applications in agricultural settings where the agronomic needs of crops are sometimes the basis for state and federal restrictions. A wide array of organic amendments, each with a different set of advantages and disadvantages, are available in most places. Table 1.2, adapted from a document produced by the US EPA, summarizes a few well-established organic amendments for soil remediation/revitalization and lists the advantages and disadvantages of each.

Table 1.2: Popular organic amendments in the Mid-Atlantic for roadside topsoil summarized by their availability, use, cost, advantages and disadvantages. This table had been adapted from Table 3 found in US EPA Report 542-R-07-013 (The Use of Soil Amendments for Remediation, Revitalization, and Reuse, 2007).

Amendment	Availability	Cost	Advantages	Disadvantages	Other:

Biosolids	Readily available, especially in urban areas	Materials sometimes free; municipalities may pay for transportation	Highly cost-effective; well characterized	Nutrient loads and moisture content vary depending on production methods	May require a permit; Odor driven concerns /complaints
Composted leaf-based yard waste	Location dependent; limited volumes and high demand	Potential high product and transport costs	Well characterized; stable product	N quantity usually significantly lower than other materials	
Uncomposted yard/wood waste	Readily available	Often free	Available in variable sizes	Highly variable products; high C:N ratio	May be used for a bulking and erosion control; source of C

With the large number of benefits that recycled organic waste products have to offer, interest in amending highway embankment topsoil with them caught the attention of the US EPA in the late 1990s/early 2000s ("Compost Use on State Highway Applications," 2005). Organizations such as the US Composting Council joined lobbying efforts to persuade states to increase the demand for compost products. These efforts were successful in some states such as Maryland, where MD Transportation Code § 8-609.3 (2014) was adopted. This law promotes the use of compost in landscaping and highway construction projects. Compliance was accomplished by specifying organic products as a design element in construction projects - for instance, as filler material in filter logs. Additionally, the Maryland Department of Transportation State Highway Administration (MDOT SHA) responded to the legislation by increasing the minimum concentration of OM in highway embankment topsoil specifications. Though the measure does not directly encourage the use of organic waste products, the agency hoped that organic amendments would be used to improve the OM content of soil that fell short of the minimum standard. In doing so, the agency also hoped to improve the general quality of highway topsoil thereby providing construction and maintenance benefits.

Highway construction frequently has a significant negative impact on both natural and cultivated soil quality, which could diminish adjacent vegetation coverage for decades (Zhao et al., 2007; Trammell et al., 2011). This happens because the soil used for embankments is engineered and graded to meet the structural requirements needed to support roads (Lim, 2014), which may be in conflict with the soil properties that best support plant life. For example, highly compacted soil provides a good base for pavement but restricts root growth.

Establishing healthy vegetation as rapidly as possible is a top priority following construction activities. This is because groundcovers, such as turfgrass reduce soil erosion, increasing roadway stability (Booze-Daniels et al., 2000). A common strategy to enhance growth is to cap off constructed soils with a topsoil layer to provide a suitable substrate for vegetative ground cover (Claassen and Zasoski, 1993). These topsoil layers are intended to be less compacted, have higher OM content, and have more of the nutrients needed to support vegetation as compared to the sublayers. Benefits may be further boosted by the addition of organic amendments to the soil to increase soil OM (Curtis and Claassen, 2009; McGrath et al., 2020).

Due to the range of products available, varied traits and the complex differences in soil characteristics, there is no national standard for organic amendments or use restrictions in roadside soil. The lack thereof is problematic since the incorrect use of organic amendments could restrict growth of highway embankment ground cover due to nutrient deficiencies caused by immobilization or inadequate supply (Barker and Bryson, 2006). On the other hand, high application rates can result in significant nutrient leaching, particularly after application (Daniels et al., 2003; Faucette et al., 2004). Given the number and complexity of factors involved, it is more feasible for state or local jurisdictions (as opposed to the federal government) to set standards for organic amendments and/or use restrictions – and many have (Kirchhoff et al., 2002).

An interdisciplinary approach should be applied when designing guidelines and best management practices for organic amendments since many stakeholders and physical/chemical factors are at play. At a minimum, considerations should include product availability, product chemical and physical properties, local soil characteristics, seasonal weather patterns (since they are known to affect mineralization patterns; Rigby et al., 2016), and regulatory restrictions that apply to health and environmental concerns. In Maryland, environmental concerns are a driving factor for determining best management practices associated with organic amendments due to the state's proximity to the Chesapeake Bay and a long history of legislation designed to protect it.

1.2 Maryland Nutrient Management and Implications for Organic Amendment Use Restrictions in Urban Soil

The Chesapeake Bay is the largest, most productive estuary in the US, and provides value that transcends those measured by biological or economic metrics (Morgan and Owens, 2001). For decades, excess sediment and nutrients from agricultural and urban sources, primarily N and P, have significantly impacted the Bay's health. These nutrients, along with potassium (K), are essential to plants and are the main ingredients in most commercial fertilizers. However, if applied at the wrong time, in the wrong manner, or in quantities that exceed plant needs, soluble and particulate bound N and P can be transferred to waterways through runoff from excess irrigation and rainwater. Phosphorus is typically the nutrient in freshwater ecosystems that limits growth. In contrast, N is the primary limiting factor in coastal marine ecosystems. Therefore, when water bodies are enriched with N and/or P, a chain reaction known as eutrophication is triggered in which plants and algae flourish and deplete systems of light and oxygen. The result is increased mortality of aquatic plant and animal life. The Chesapeake Bay Program estimated that agriculture, followed by sediment loss from developed land, and wastewater treatment plants were the three largest non-natural sources of N and P pollution between 1985 and 2022 (Chesapeake Progress, 2023). To address such non-point sources of N and P pollution, Maryland's Nutrient Management Program (NMP) imposes requirements and restrictions on farmers, lawn care professionals, and even homeowners to prevent excess nutrients from non-point source pollution from entering the Bay.

Water pollution was first addressed by Congress through passage of the Federal Water Pollution Control Act of 1948. After a fierce debate between congressional members, the bill was limited to interstate waters and restricted the role of the federal government in enforcing pollution control measures. The Water Pollution Control Act was then amended in 1972 to address these and other shortcomings. The revised bill is known as the Clean Water Act (CWA), which was further amended and stands today as the basis for national water pollution control measures. The CWA built a framework for regulating pollutant discharges into the waters of the US and included quality standards for surface waters. Additionally, the CWA gave the EPA the authority to implement and oversee pollution control programs, later to include the Chesapeake Bay Program (through a 2009 Presidential Executive Order, discussed later). Originally, the CWA focused on pollutant discharges from point sources (e.g., sewage treatment plants) through a permit program called the National Pollutant Discharge Elimination System. Nevertheless, the CWA recognized the need to address non-point (dispersed) sources of pollution. By the late 1990s, the EPA began focusing on addressing those sources, including runoff from agricultural and urban areas. At the same time, the EPA emphasized wetland protection under the CWA. In 2000, new CWA rules were introduced that encouraged states to establish Total Maximum Daily Load (TMDL) standards and plans for meeting those targets.

The Maryland Department of Agriculture (MDA) with help from University of Maryland Extension (UME) established the Maryland Nutrient Management Program in 1989 to help farmers voluntarily reduce non-point source nutrient pollution, by reducing fertilizer rates and more precisely timing and placing fertilizers appropriately. Voluntary compliance ended in 1998 when the Maryland Water Quality Improvement Act (WQIA) was passed. The WQIA mandated nutrient management plans for farmers and regulated commercial fertilizer applications on non-agricultural land (Simpson, 1998). Additionally, the WQIA established turfgrass fertilizer requirements which were based on University of Maryland (UMD) guidelines. A decade later, the Chesapeake Bay Phosphorus Reduction Act of 2009 (Maryland HB609) was passed. The law restricted the P content of turfgrass fertilizer and imposed requirements on manufacturers selling fertilizer in Maryland.

As Maryland's nutrient management program evolved, EPA oversight of the Chesapeake Bay Program influenced nutrient management regulations. The goal of the Chesapeake Bay Program, which persists today, is to restore the health and productivity of the Chesapeake Bay alongside the six watershed states and the District of Columbia. Despite some States' efforts, the EPA determined that progress to restore Bay health was insufficient as poor water quality persisted in the Bay and its tributaries. In 2009, President Obama issued an executive order (EO 13508) that called on the federal government to renew the effort to protect and restore the watershed. That same year, the Chesapeake Executive Council set short-term restoration goals—called two-year milestones—to hasten restoration and increase accountability. This led the EPA to establish the Chesapeake Bay TMDL on December 29, 2010. Subsequently, participating members of the Chesapeake Bay Program set new pollution reduction targets for specific sources, including agriculture and stormwater, based on the Bay's TMDL. These targets are outlined in the Chesapeake Bay Watershed Agreement, which was last renewed on June 16th, 2014.

Soon after passage of the Chesapeake Bay Phosphorus Reduction Act of 2009 and influenced by the newly established Chesapeake Bay TMDL, members of the Chesapeake Bay Commission introduced legislation to reduce pollution from lawn fertilizers applied to homes, golf courses, and businesses. Subsequently, the Fertilizer Use Act of 2011 (Maryland HB573) was signed into law on May 19, 2011 by Maryland Governor, Martin O'Malley. This law stands today (amended) and pertains to anyone who fertilizes non-agricultural turf, including homeowners by restricting the amount of N and P that can be applied as well as the dates for fertilizer applications. Notably, the law applies to fertilizers as well as organic sources of N and P in order to curb non-point source pollution from urban sources.

The intent of Maryland's fertilizer law is to help homeowners and lawn care professionals maintain healthy lawns without applying unnecessary N and P. It is written in a way that requires the Maryland Department of Agriculture (MDA) to consult with UMD to develop a public education program, soil testing guidelines, and fertilizer recommendations (MD Code, Agriculture §8–803.7). Additionally, UMD is required to review turf fertilizer recommendations every three years and revise them as necessary, with consideration of plant nutrient requirements.

Beginning in 2019, MDOT SHA partnered with UMD to improve specifications for compost and compost amended topsoils. Because organic amendments are stipulated in

Maryland's fertilizer law, UMD recommendations to MDOT SHA must fall in line with fertilizer law restrictions. Yet, the fertilizer law is written in such a way that the restrictions are based on UMD's recommendations. This linkage provides the university an opportunity to affect not just how organic products are used on highway embankment topsoil, but disturbed and manufactured soils in general where they are used to effect turfgrass establishment. This unique situation also allows the university to influence others outside of Maryland to adopt guidelines for organic amendments that limit nutrient pollution, since other States look to Maryland as a leader in nutrient management regulations that protect the environment.

1.3 Dissertation Overview

To accomplish the goals outlined by the UMD/MDOT SHA research team through a funded project, the first phase of research described in this dissertation involved identifying the constraints that determine organic product selection in MDOT SHA topsoil (Chapter 2). This was accomplished through a series of interviews with manufactured topsoil producers and MDOT SHA landscape division employees. Results from the interviews were compared with empirical data garnered from topsoil samples provided by interview participants as well as MDOT SHA soil test results. Analysis of the data identified which organic waste products are most likely to be used in state highway soil, which set the stage for the next phase of the research.

After determining which products to focus on, the research team conducted two greenhouse microcosm studies that measured plant growth responses and nutrient losses for soils amended with either composted yard waste, wood mulch, or biosolids. My role on the team was to evaluate turfgrass performance and efficiency of amendment applications when the treatments were applied in accordance with MDOT SHA specifications for "furnished topsoil" – meaning soil that is blended offsite into a topsoil like consistency. A fellow graduate student, whose complementary research is currently in preparation (Pamuru et al., in preparation), provided the analysis of leachates which were collected from the microcosms during simulated rain events. To assess N and P efficiency, leachate mass losses were compared to soil test results and plant tissue concentrations. Nutrient efficiencies are summarized in Chapter 3.

Results from the UMD/MDOT SHA research project prompted further investigation of biosolid use in relation to turfgrass establishment. In a second round of experiments, the nutrient loading rates and leaching potential of four biosolids amendments were assessed in another microcosm study. The effects of the same amendments on turfgrass growth and nutrient leaching from amended soil in a field experiment, were measured when the amendments were applied at the current UMD recommended rate for turfgrass establishment. Results from these two biosolid studies are summarized in Chapters 4 and 5. Chapter 5 concludes with my recommendations for biosolid amendments used in conjunction with turfgrass establishment. It is my hope that the university will consider incorporating those recommendations into future recommendations, in partnership with MDA and MDOT SHA.

1.4 Dissertation Objectives

The overarching objectives for the research described in this dissertation were:

- To provide specific guidelines to MDOT SHA to improve compost usage in highway topsoils
- To provide validated research evidence of which organic waste products should be used in Maryland urban and manufactured soils
- To determine the effects of the most frequently used organic amendments on turfgrass establishment, in order to improve MDOT SHA topsoil specifications
- To determine what effect biosolids amendments have on turfgrass establishment and nutrient losses when they are used at UMD’s recommended rate for organic products

- To assess whether UMD’s current recommendations for turfgrass establishment need to be re-evaluated, to include limitations for biosolids amendments to minimize unnecessary nutrient losses

Chapter 2: Evaluation of Maryland State Highway Administration's compost usage efforts and effects on product selection, soil fertility, and nutrient mobilization

2.1 Introduction

2.1.1 Properties of Roadside Soil

Highway construction greatly disturbs soil physical, chemical and hydrological properties. These negative impacts on soil chemical and physical properties can result in poor roadside vegetation establishment, enhancing stormwater runoff and erosion (Deljouei et al., 2018; Seutloali and Beckedahl, 2019). Typical undisturbed soil profiles are characterized by highly distinct layers, including a loose partially decayed organic layer (O horizon) that is located above a 6 – 20 cm thick mixed mineral and humus layer (known as topsoil or the A horizon). Combined, these layers are rich in nutrients, air and water – the essential components needed to support vegetation. When land is disturbed and graded for highway infrastructure, vegetation is removed and the natural attributes of the upper soil horizons are greatly reduced or lost as soil layers are blended with less fertile subsoil. Following grading activities, roadside soil is commonly characterized by one or more of the following negative properties, all of which impact plant establishment: low concentration of OM, insufficient nutrients in the root zone, low electrical conductivity, high proportion of sand and gravel, and high compaction/bulk density (Johnston and Johnston, 2004; Tan et al., 2013). Imported subsoil used as backfill exacerbates these issues. Because a healthy vegetative cover is essential for protecting highway shoulders and embankments from erosion, transportation agencies frequently mandate efforts to improve soil fertility. The purchase of furnished topsoil (as defined by MDOT SHA - a natural, friable, blend of surface soil from various locations that is uniform in color and texture) to supplement existing topsoil is one such method. Incorporation of organic amendments is another method (Brown and Gorres, 2011). These methods are commonly used in conjunction with each other.

2.1.2 Organic Amendments

Organic matter improves the physical and chemical properties of soil and is a component of common waste products such as compost and biosolids (Larney and Angers, 2012). Such products are regularly used in agricultural production as soil amendments to increase fertility and water holding capacity. Incorporation of composts and biosolids into soil expands the circular economy while easing mounting environmental and waste management strains. Furthermore, land application reduces methane production at landfill sites and decreases agricultural dependency on fertilizers (Sharma et al., 2019). However, unintended consequences such as soil salinization, pH imbalances, phytotoxicity, or excessive nutrient leaching could result if use is unrestricted. This is because some sources of OM are high in nutrient contents, particularly nitrogen (N) and phosphorus (P) (Alvarenga et al., 2015), and mobility can be highly variable.

2.1.3 Regulatory Influences

It has become increasingly clear that products that enhance soil fertility should be restricted to prevent unintended nutrient runoff issues. Maryland is particularly mindful of non-point source agricultural and urban N and P pollution due to their association with eutrophication and the State's ongoing efforts to protect and restore the Chesapeake Bay. After passage of the Maryland Water Quality Improvement Act in 1998, nutrient reduction goals in the early 2000s were focused on agricultural operations (Lea-Cox and Ross, 2001). The following decade, the Fertilizer Use Act of 2011 was designed to reduce pollution from fertilizers applied to non-agricultural turf and landscapes in Maryland. This law stands today (as amended) and pertains to anyone who fertilizes new and existing turf stands, including homeowners and landowners such as MDOT SHA, restricting the total amount of N and P that can be applied, as well as seasonal application restrictions. Notably, the law also applies to organic sources of N and P, but limitations on organic applications are only triggered when they are *surface* applied, not incorporated. Restrictions for incorporated organic materials (considered soil amendments) are based on volume (not weight), regardless of the source material and nutrient content.

In an effort to increase compost usage, Maryland passed 2014 HB878 (State Highway Administration - Compost and Compost-Based Products - Specification). This bill established the use of compost and compost-based products as a best management practice for pollution control and required MDOT SHA to update material specifications as necessary. In response, MDOT SHA amended furnished topsoil specifications to include a minimum OM content of 4% (8% maximum), to encourage the use of compost products (Standard Specifications for Construction and Materials, 2021). Additional MDOT SHA topsoil standards are summarized in Table 2.1. Compliance with the OM standard became mandatory at the end of 2019. In 2021, the pH standard was expanded from a max value of 7.2 to 7.4.

Many different OM amendments are used to increase soil OM contents. Depending on the source material and age or composting status, OM amendments can affect soil pH and increase the concentration of soluble salts in soil (Butler and Muir, 2006; Hosseinpur and Pashamokhtari, 2013). Consequently, compliance with MDOT SHA's furnished topsoil standards may be compromised when amendments are added to meet the OM standard (Table 2.1). Furthermore, research shows that high rates of organic amendments restore degraded soil but may cause excessive losses of soluble N and P through leaching (Daniels et al., 2003;

Paramashivam et al., 2017; Hurley et al., 2017). Therefore, a better understanding of the base OM components used to meet MDOT SHA's OM standard for topsoil is needed to improve current specifications where necessary.

Table 2.1: MDOT SHA standards for soil pH, organic matter, and max soluble salts for Existing & Salvaged Topsoil and Furnished Topsoil *("Standard Specifications for Construction and Materials," 2023)*. Particle size distribution requirements are not included.

	Soil pH	OM (%by weight)	Max Soluble Salts (mmho/cm)
Existing & Salvaged	4.8 - 7.6	1.0 - 8.0	1.25 (800 ppm)
Furnished	6.1 - 7.4	4.0 - 8.0	0.78 (500 ppm)

2.1.4 Research Objectives

This research explores MDOT SHA's furnished topsoil guidelines and the effects of compost amended topsoil (CAT) on soil properties and vegetation establishment, to ensure responsible use of incorporated amendments. This study had the following specific objectives:

1. To identify the products used in MDOT SHA furnished CAT blends supplied by contractors, including factors that impact OM selection, to improve specifications for highway construction projects, expand compost usage, and reduce potential issues such as poor nutrient availability, unnecessary nutrient losses, and failures to establish vegetation.
2. To characterize Maryland furnished topsoil products by their physical and chemical properties to determine if raising the minimum OM standard for furnished topsoil had any significant effects on those properties.
3. To conduct a preliminary assessment of nitrogen and phosphorus concentrations in leachate generated from MDOT SHA specified furnished topsoil, to determine if initial nutrient leachates are of concern, based on reported amendment inclusions.

2.2 Materials and Methods

2.2.1 Interviews

Institutional Review Board (IRB) approval was granted in June 2020 to conduct interviews with Maryland topsoil dealers and compost producers. Invitations for participation in the research project were extended to the 41 businesses included on the 2020 MDOT SHA List of Qualified Producers/Manufactures for Furnished Topsoil and Compost Materials. Contractors are required to submit the intended source of materials for highway construction projects. Submission occurs through a system developed by MDOT 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 topsoil dealers that accepted the invitation to participate in the study, five were ranked in the top ten of intended suppliers and three were ranked in the top five.

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 MDOT 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. The interview questions asked of topsoil producers and compost manufactures are included in Appendix A. All interviews were conducted via Zoom, recorded with permission and later transcribed into Microsoft Word documents.

2.2.2 Analysis of MDOT SHA Soil Tests

When this study began in the fall of 2019, topsoil producers were required to submit quarterly soil samples to Matrix Sciences (Chicago, IL), formerly, AgroLab, (Harrington, DE) to establish and/or maintain inclusion on the qualified producer list, based on compliance with furnished topsoil standards. In 2021, MDOT loosened the quarterly requirement for testing to every 6 months. At that same time, the MDOT Office of Materials Technology laboratory (OMT) took over soil testing. Records were obtained for 2018-2021 to determine if increasing the OM standard affected the mean concentration of OM, pH and concentration of SS for furnished topsoil. Matrix Sciences measured electrical conductivity (mmho/cm) to determine salinity; however, OMT did not. Therefore, mean comparisons for SS only include the measurements between 2018 and 2020. Statistical analyses were performed using SPSS version 29 (IBM Corp., Armonk, NY). After confirming that the homogeneity of variability was met, a one-way analysis of variance (ANOVA) was run to determine if yearly mean differences were significant. Tukey's HSD was used for post hoc analyses.

2.2.3 Characterization of Maryland Furnished Topsoil Samples

All interview participants were asked to donate a furnished topsoil sample for independent analysis. Ten soil producers agreed and voluntarily disclosed the type of soil amendments used (if any) to meet MDOT SHA topsoil specifications for furnished topsoil. The samples were collected in the fall of 2020. Three of the ten samples were not amended with OM, three samples were amended with leaf-compost, two were amended with finely shredded wood mulch, one was amended with mushroom compost, and one was amended with a combination of finely shredded wood mulch and biosolids. In each case, wood mulch was derived from finely ground hardwood tree waste.

Samples were analyzed for OM (loss on ignition; Schulte and Hoskins, 2011), EC (1:2; Gartley, (2011)), and texture by the UMD Environmental Engineering Laboratory. Samples were sent to Matrix Sciences to be analyzed for pH (1:1 soil:water; Eckert and Sims (2011)), cation exchange capacity (summation; Ross and Ketterings, (2011)), organic carbon (combustion; Nelson and Sommers, (1996)), total nitrogen content (combustion; Bremner, 1996) extractable phosphorus (ICP; Mehlich, (1984)), and total phosphorus content ("Method 3050B: Acid digestion of sediments, sludges, soils," 1996).

2.2.4 Column Study Experimental Design

Each of the 10 topsoil samples provided by interview participants was included in a short-term column nutrient leaching study to determine the loss of nitrogen (N) and phosphorus (P) when the soils were leached with three aliquots of deionized water during simulated rain events (SREs). 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 sample replicates (Table 2.2). After soil was sieved and before the start of the first leaching event, 100 mL of each soil sample was preserved at -10° C until they were shipped to Matrix Sciences for characterization analysis as described above. 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 (Figure 2.1). Before loading samples, a clean

WhatmanTM 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 - the average topsoil depth applied on MDOT SHA roadsides. Total substrate volume for each column was 1,111 cm^3.

Table 2.2: Average soil column bulk density and standard deviation (SD) for 6 replicates of 11 topsoil treatments.

Sample*	Bulk Density ($g \cdot cm^{-3}$)	SD
A	1.16	0.01
B	1.09	0.01
C	1.20	0.02
D	1.05	0.02
E	1.18	0.03
F	1.18	0.01
G	1.29	0.03
H	1.23	0.02
I	1.02	0.03
J	1.10	0.03

* Samples B, F and H were unamended. Samples A and G were amened with finely screened wood mulch. Samples C, D, and E were amended with composted yard trimmings and sample J was amended with screened wood mulch and biosolids.

To allow water to be evenly distributed, a plastic drain coupling holding a metal end cap sat on 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 clean 500 mL Büchner vacuum flasks. A vacuum system was constructed to aid drainage when columns failed to drain, which may have been due resettlement of fine particles near the base of columns. 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. Negative pressure was applied when columns failed to drain completely within 1 hr.

A total of 101.6 mm of deionized water (DI) was applied over three SREs. The volume of water applied (550 mL) for the first SRE simulated a 50.8 mm rainfall event. In subsequent rounds (2), 275 mL of DI was applied to simulate further 25.4 mm rain events. For each SRE, leachate samples (3 per column) were collected in 20 mL plastic scintillation vials. Before the samples were frozen, 50 µL of concentrated H_2SO_4 (sulfuric acid) were added to each vial. The vials were stored at -10°C until the samples were analyzed (within six months). Total nitrogen (TN) was measured using the high temperature/catalytic combustion oxidation method (720°C) on a Shimadzu TOC-L analyzer. The method detection limit (MDL) for TN was 0.1 mg·L^{-1}. To prepare samples for analysis of orthophosphate (Ortho P), approximately 20 mL of each sample was filtered through a 0.22 µm membrane to remove particulates. For total phosphorus (TP), unfiltered aliquots of each sample (25 mL) were digested in a HotBlock™, following the EPA method 365.1 for digestion. Prepared samples were analyzed on a SEAL AQ300 Nutrient Analyzer for Ortho P (MDL = 0.01 mg·L^{-1}). The volume of leachate collected in each flask was recorded at the end of each round to normalize nutrient mass loss calculations (concentration × leachate volume).

Figure 2.1. A column study was conducted to determine nitrogen and phosphorus loses from Maryland Department of Transportation specified furnished topsoil, used for vegetation establishment along road shoulders. Columns were loaded with soil to a depth of 10.16 cm and received a total of 1.1 L of deionized water, the equivalent of 101.6 mm of simulated rainfall.

2.3 Results and Discussion

2.3.1 Interviews and Analysis of SHA Soil Tests

All but two survey participants obtained topsoil from sites undergoing development (Question 1). Exceptions included a producer who blended a topsoil-like product from aggregate mining waste and organic materials. The other participant mixed discarded soil supplied by landscape contractors with an organic amendment to make MDOT SHA specified furnished topsoil. Organic matter was sourced from the materials listed in Table 2.3 (Question 2). The majority of participants preferred to use composted yard trimmings (leaf mulch). However, they explained that a combination of organic products is often used due to the cost of leaf mulch, high demand, and limited seasonal availability of leaf mulch.

Other major factors which determine the organic amendments chosen were then further explored (Questions 3 & 4, Appendix A). Cost is the predominant factor (reported by 8 producers), followed by product availability (4), quality (4), consideration of MDOT 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 of cost, availability is often 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. Furthermore, 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 or low cost to save landfill space. In general, but not always, producers shred wood mulch to a fine consistency and age (but do not actively compost) the resulting product before using it as a soil amendment.

Table 2.3: Source for organic matter used to amend furnished topsoil

Source	Number Reported	Commercial Products* (Maker, Number Reported)
Composted leaf mulch/yard trimmings	8	Leafgro® (Maryland Environmental Service, 4) Soilmate ® (Loudoun Composting, 2)
Wood mulch (sometimes aged)	5	-
Mushroom compost	1	-
Manure	1	-
None used	3	NA

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

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 MDOT SHA jobs. Moreover, three producers seek and stockpile topsoil that meets furnished topsoil standards to avoid having to add OM. Of those unlikely to add OM, all were in the top ten and two of the three seeking/stockpiling MDOT SHA spec soil are in the top five.

To better understand how incorporating organic amendments affects furnished topsoil, soil producers were asked to identify the factors taken into consideration when adding OM (Question 4, Appendix A). 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, Appendix A). Keeping in mind that some producers avoid using low OM soil (i.e., < 4% OM), they reported that organic amendments raise pH, raise the concentration of soluble salts (SS), and raise the measured 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 an additional research inquiry sparked by these interviews, quarterly (and later, bi-annual) soil tests submitted in accordance with MDOT SHA Qualified Producer requirements for 2018 – 2021 were analyzed to determine if raising the minimum OM concentration to 4% (by weight) for furnished topsoil had an effect on the mean concentration of OM, pH, and/or the concentration of SS (Table 2.4). Compliance with the SS standard was nearly 100% for each year reported. However, results indicate that mean pH significantly increased after the 4% rule took full effect (Dec 2019) and fewer producers met the specification for pH in subsequent years. Although the 2021 OM mean was statistically lower than the 2018 mean, a difference that could be attributed to the 2021 lab change, the mean OM concentration fell each year after 2018. Regardless, fewer producers met the OM specification for furnished topsoil in 2021 than in previous years (Table 2.5), indicating that implementation of a minimum 4% OM standard did not increase the overall OM concentration in furnished topsoil.

Table 2.4: Concentrations for OM (% by weight), pH and electrical conductivity (EC) of topsoil samples, which were submitted in accordance with the requirements established by the Maryland Department of Transportation State Highway Administration for inclusion on the Qualified Products List for furnished topsoil between 2018 and 2021. Results are reported as means ± SE. Rows with different letters are significantly different ($\alpha = 0.5$).

	2018 (n = 86)	**2019** (n = 106)	**2020** (n=106)	**2021** (n = 50)	**P-value**
OM (%)	5.94±0.22b	5.59±0.10b	5.43±0.17b	4.31±0.22a	<0.001
pH	6.7±0.07a	6.8±0.06a	7.1±0.06b	7.1±0.08b	<0.001
EC (mmho/cm)	0.23±0.02	0.27±0.02	0.27±0.02	NA*	0.210

* EC was not collected during this period.

Table 2.5: Percent of furnished topsoil tests submitted by Qualified Producers which met the Maryland Department of Transportation State Highway Administration's 2021 specifications for organic matter content (OM), pH, soluble salts, and all three categories (combined).

	2018	2019	2020	2021
OM	59	63	63	46
pH	70	73	63	66
Soluble Salts (EC)	98	98	96	NA*
Combined	40	42	30	NA*

* Soluble Salt data for 2021 not available

Having topsoils meet agency standards before it is transported to the construction site is common. However, making adjustments to soil offsite has benefits as well as drawbacks. The major benefit is that amendments can be thoroughly incorporated during the mixing process, resulting in a homogenous substrate which gives rise to uniform vegetative coverage (barring physical variables in the landscape). The major drawback to incorporating amendments offsite is that the time between blending and placement at the final destination could be consequential in terms of nutrient composition. Chemical and biological processes that may reduce the concentration of OM or result in the intended pH to be over or undershot will continue while substrates are stockpiled (Abdul-Kareem and McRae, 1984). The longevity of the benefits received from applying amendments depends on the product, the total acidity, the amount of OM present, and the clay content (Bast, 2015). To ensure that the target pH range is achieved and the benefits of OM are realized, roadside managers should test and/or amend furnished soil shortly before transport to final destination so that adjustments can be made immediately before transport or onsite before seeding if necessary.

Despite their high OM and nutrient content, low cost and widespread availability, only two producers' amendments contained biosolids at the time interviews were conducted. One producer reported using a composted green-waste product from outside MD that included biosolids when local composted yard waste was not available. The other producer used biosolids mixed with mulch in topsoil sold for agricultural purposes, but not for MDOT-SHA projects. Five producers expressed interest in biosolids due to availability or low cost. However, the following concerns kept them from using biosolids at that time: high SS concentration, perception of high pH, potential regulatory requirements associated with transportation and storage, feasibility of onsite storage, odor, and the high moisture content of some biosolids which could make them difficult to mix. At least three producers were willing to experiment with biosolids to improve the quality of furnished topsoil if guidance became available.

2.3.2 Characterization of Maryland Furnished Topsoil Samples

Results from the analysis of the topsoil samples (n = 10) donated by interview participants are summarized in Table 2.6. Out of the ten topsoil samples collected, three were unamended (F, H, I); three were amended with leaf-compost (C, D, E); two were amended with finely shredded wood mulch (A, G); one was amended with mushroom compost (B), and one was amended with a combination of finely shredded wood mulch and biosolids (J). Each soil met furnished topsoil textural requirements (% sand, % silt and % clay). Statistically, all furnished topsoil samples met the minimum mean (±SD) requirement for OM (i.e., 4%). The SS requirement (EC < 0.78 mmhos/cm) was met by all except the soil amended with mushroom compost. Six of the soils met the pH standard (6.1-7.4) and four exceeded it, including three amended soils, which support concerns raised by interview participants that OM additions make overall compliance with furnished topsoil requirements harder to achieve.

Parameters that are not listed in the MDOT SHA specifications, such as cation exchange capacity (CEC) and measures for N and P content were analyzed to evaluate soil fertility and to provide context for the column study leachate results. A high Mehlich-3 P (M3P) sufficiency level for turfgrass establishment is > 55 mg·kg^{-1} and 27 - 54 mg·kg^{-1} defines the medium sufficiency level (Carrow et al., 2001). Two soils (an unamended and one amended with mulch) had low P sufficiency ratings (< 27 mg·kg^{-1}). Three soils (an unamended, a leaf compost-amended and the mushroom compost-amended soil) had high sufficiency ratings. The CEC for soil amended with mushroom compost (30.4 meq/100g) was more than twice any other sample, which ranged from 8.5 – 16.8 meq/100g. The N and P-content (TN and TP) for mushroom amended soil was also very high (2210 mg·kg^{-1} of TN, 229 mg·kg^{-1} of M3P and 2210 mg·kg^{-1} of TP) compared to others which ranged from 10 -734 mg·kg^{-1} of TN, 8 - 70 mg·kg^{-1} of M3P, and 20 - 650 mg·kg^{-1} of TP, respectively. While N and P are needed for plant growth, excess organic and inorganic nutrient contents are susceptible to release under the right conditions. For instance, N species are vulnerable to transport through subsurface leachate when the nitrification potential is high and when the CEC is low (Qian and Cai, 2007). On the other hand, P is generally retained in soil by inorganic constituents. However, soils with high P-saturations are susceptible to orthophosphate losses as well as organic-P losses, which have been shown to move faster through soil profiles (McDowell et al., 2021).

Table 2.6: Soil property summary for the ten furnished topsoil samples donated by interview participants. Summary includes; concentration of organic matter (OM), pH, electrical conductivity (EC), cation exchange capacity (CEC), organic carbon (organic-C), Mehlich-3 P (M3P), total phosphorus (TP), total nitrogen (TN), and texture.

ID	Amendment	OM*	pH	EC*	CEC	Organic C	M3P	TP	TN	Texture*
		%		mmhos/cm	meq/100g	%	--------	$mg{\cdot}kg^{-1}$	--------	
A	Screened Wood Mulch	3.81±0.35	7.1	0.49±0.02	10.5	1.83	30	294	20	Sandy Clay Loam
B	Mushroom Compost	8.93±0.32	7.4	2.69±0.22	30.4	3.48	229	2210	2210	Silt Loam
C	Soilmate ® (Leaf Compost)	5.89±0.29	7.3	0.22±0.05	15.5	2.29	31	376	319	Sandy Clay Loam
D	Leaf compost	6.74±0.16	7.7	0.23±0.03	16.3	2.61	70	553	520	Sandy Loam
E	Leafgro ® (Leaf Compost)	5.32±0.28	7.8	0.21±0.03	11.8	1.86	29	236	58	Sandy Loam
F	None	3.96±0.12	6.8	0.25±0.14	8.5	1.44	70	650	35	Sandy Loam
G	Screened Wood Mulch, Sulfate, and Sand	5.1±0.8	6.8	0.55±0.12	12.6	1.96	8	351	45	Sandy Clay Loam
H	None	4.15±0.14	7.2	0.16±0.03	11.7	1.31	8	213	10	Silt Loam
I	None	7.44±0.68	7.7	0.19±0.03	14.2	3.56	31	448	734	Sandy Loam
J	Screened wood mulch and Bloom ® (possibly manure too)	7.4±0.26	7.5	0.22±0.01	16.8	2.49	47	634	551	Sandy Clay Loam

* Processed in the UMD Environmental Engineering Laboratories in triplicate; results are expressed as or mean ± SD. All other data provided as single measurements by Matrix Sciences (Chicago, IL).

2.3.3 Column Study

Leachates from the column study were analyzed for TN, TP, and (soluble reactive phosphorus) ortho-P. Concentration averages for TN are summarized in Figure 2.2, while TN mass loss averages are provided in Figure 2.3. It should be noted that the moisture content of the soil differed between samples, which affected leachate volume. Thus, mass loss (concentration × leachate volume) for the first run is not reported. Rather, cumulative mass loss for all three runs is shown since each sample was fully saturated after the first run.

The relationships between amendments and nutrient leaching patterns were not clear based on the results of the column study, as producers did not report the rates ($kg\cdot m^{-3}$) at which amendments were incorporated, which was not required by MDOT SHA at the time this research was conducted. Without knowing these incorporation rates, deciphering the results was difficult. 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 $mg\cdot kg^{-1}$) and the highest mass loss of TN via leachate. However, sample G (amended with mulch) leached >2× more TN than the other eight samples, but had a soil TN concentration of only 45 $mg\cdot kg^{-1}$. On the other hand, samples D, I, and J had the lowest leachate TN concentrations despite having over 500 $mg\cdot kg^{-1}$ of soil TN. Excluding samples B and G, all other samples lost on average less than 16 mg of TN after 101.6 mm of deionized water was applied to the columns. Sample J, amended with biosolids and mulch, lost the least amount of TN (0.38 mg-N). The standard deviation for TN run averages for sample G was high, 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.

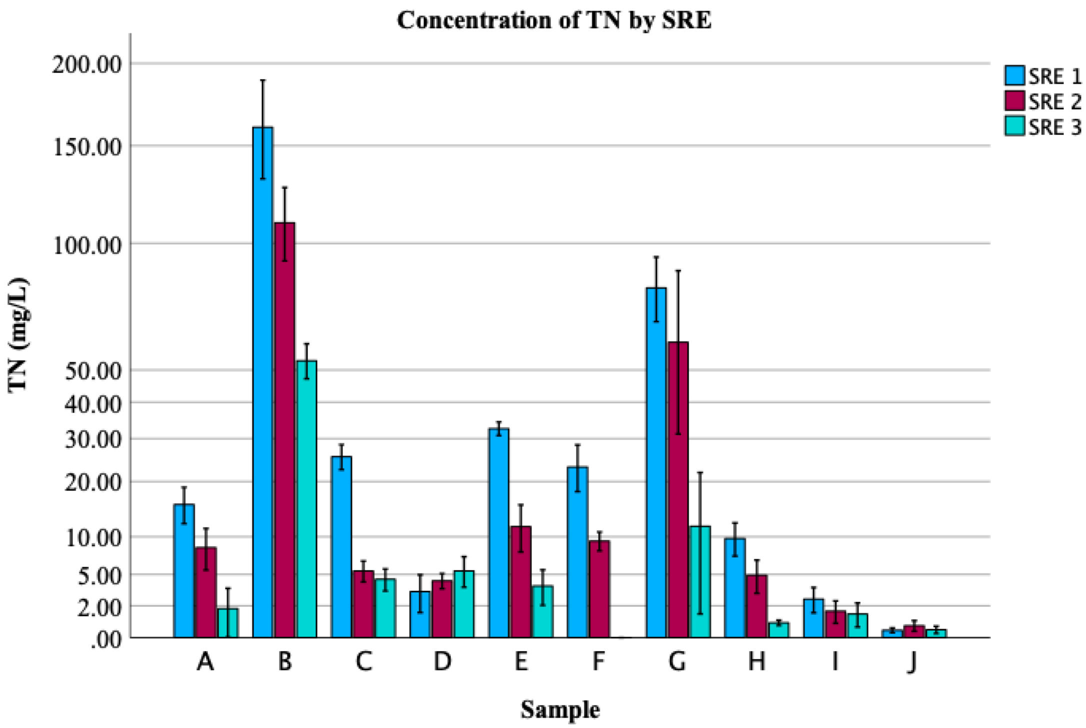


Figure 2.2. Average Column Study leachate total nitrogen (TN) concentrations for ten furnished topsoils by simulated rain event (SRE). Error bars represent SD.

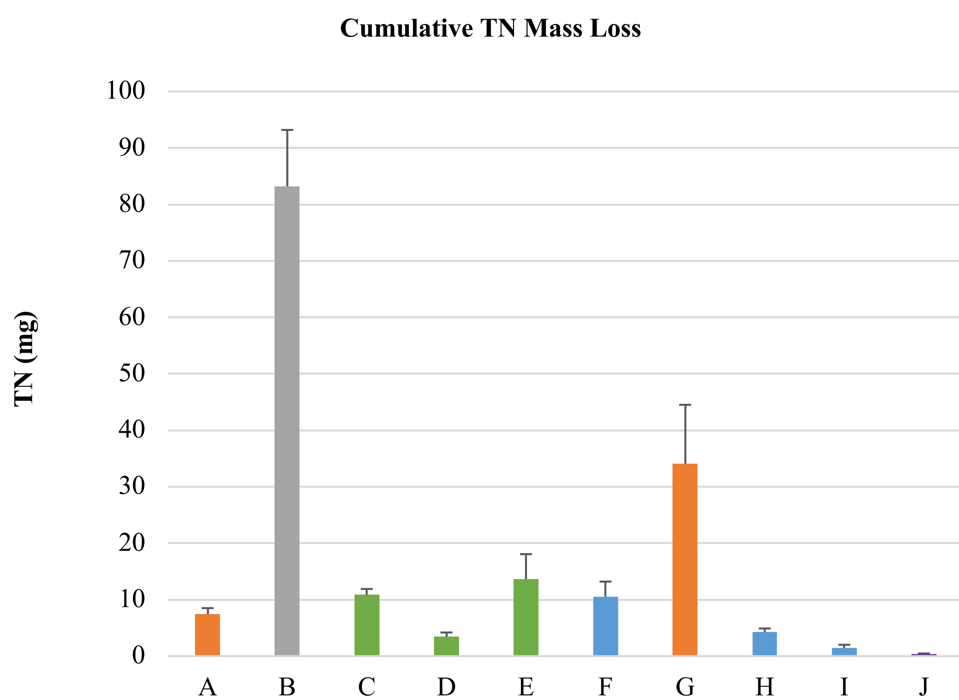


Figure 2.3. Average Column Study cumulative mass loss of total nitrogen (TN). Error bars represent SD.

Concentration averages for ortho-P and TP for each SRE are summarized in Figures 2.4 and 2.5, respectively. Additionally, a comparison of TP and ortho-P concentrations in the first SRE is given in Figure 2.6 for closer investigation since research shows that losses are generally highest after incorporation (Faucette et al., 2005). Finally, cumulative TP mass loss averages are summarized in Figure 2.7.

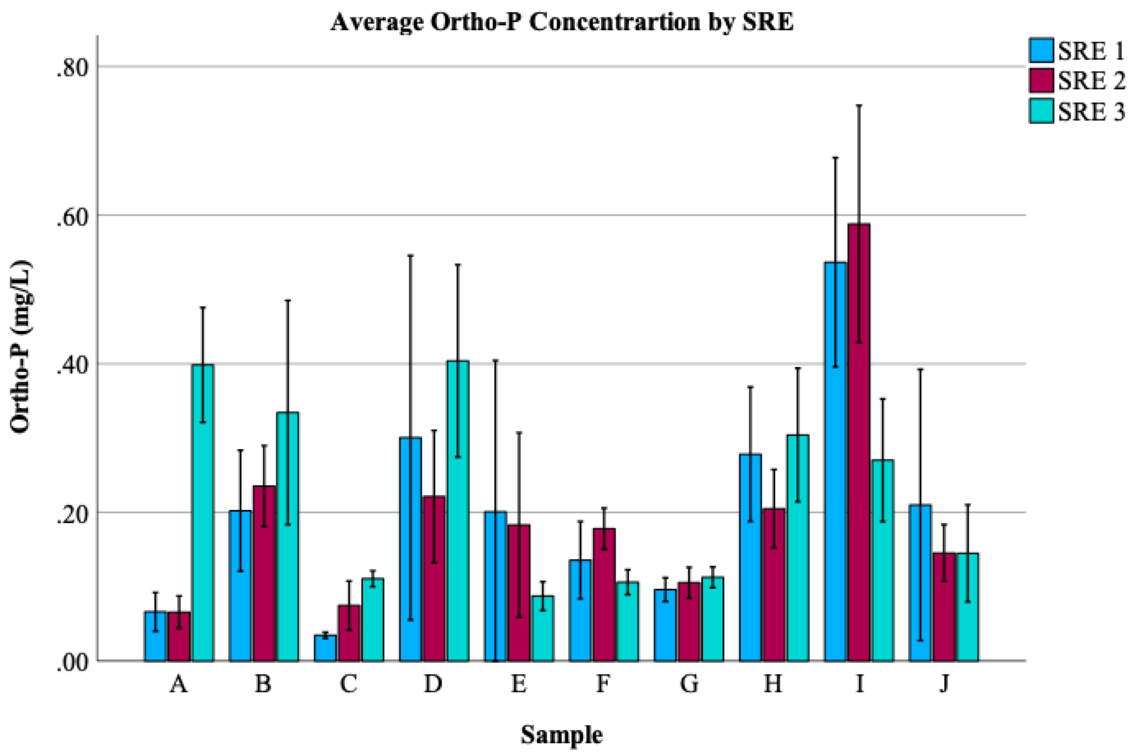


Figure 2.4. Average Column Study leachate ortho-P concentrations for ten furnished topsoils by simulated rain event (SRE). Error bars represent SD.

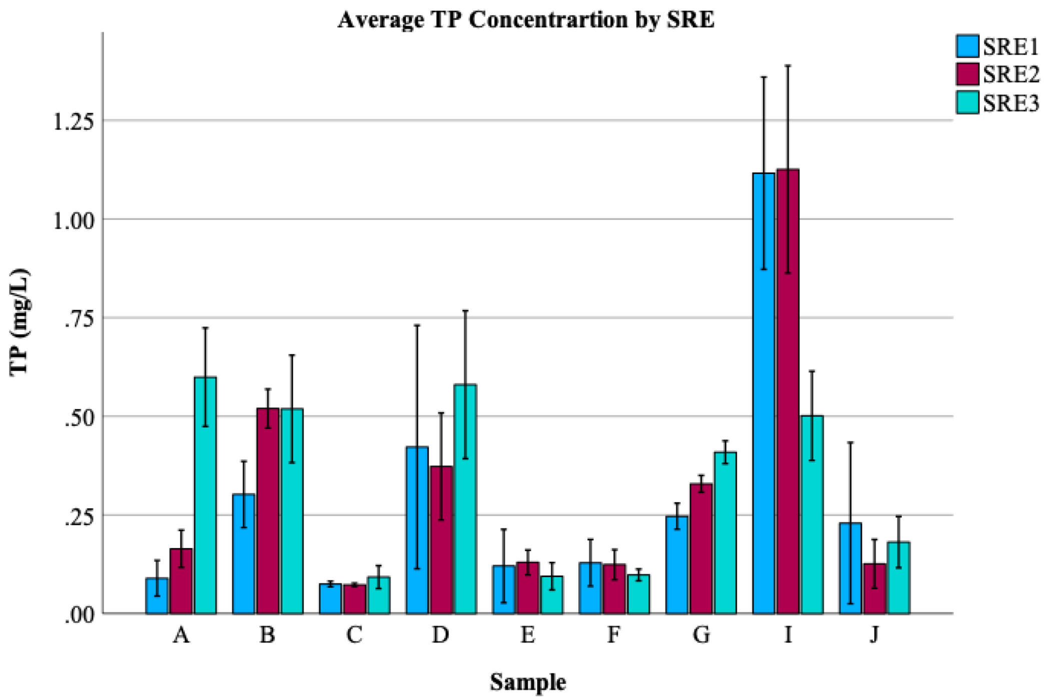


Figure 2 5. Average Column Study leachate total phosphorus (TP) concentrations for nine furnished topsoils by simulated rain event (SRE). Data for H not available. Error bars represent SD.

Reconciling soil P analysis results with leachate P results was also difficult. Sample I had the greatest concentration of ortho-P and TP in the leachate, followed by samples D and B (Figures 2.4-2.5). The average mass loss of TP from I (0.73 mg-P) was more than double the averages of samples B and D (approximately 0.36 mg-P each). Sample I was not amended but B and D were with mushroom compost and leaf compost, respectively. The amount of ortho-P to TP was comparable for most samples meaning that the majority of P in leachate was dissolved in an inorganic form (Figure 2.6). The exception was sample I, an unamended soil, in which half of the TP was 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. Samples B and D had high concentrations of M3P in the soil (229 mg·kg^{-1} and 70 mg·kg^{-1}, respectively), while sample I had 31 mg·kg^{-1} (Table 2.6).

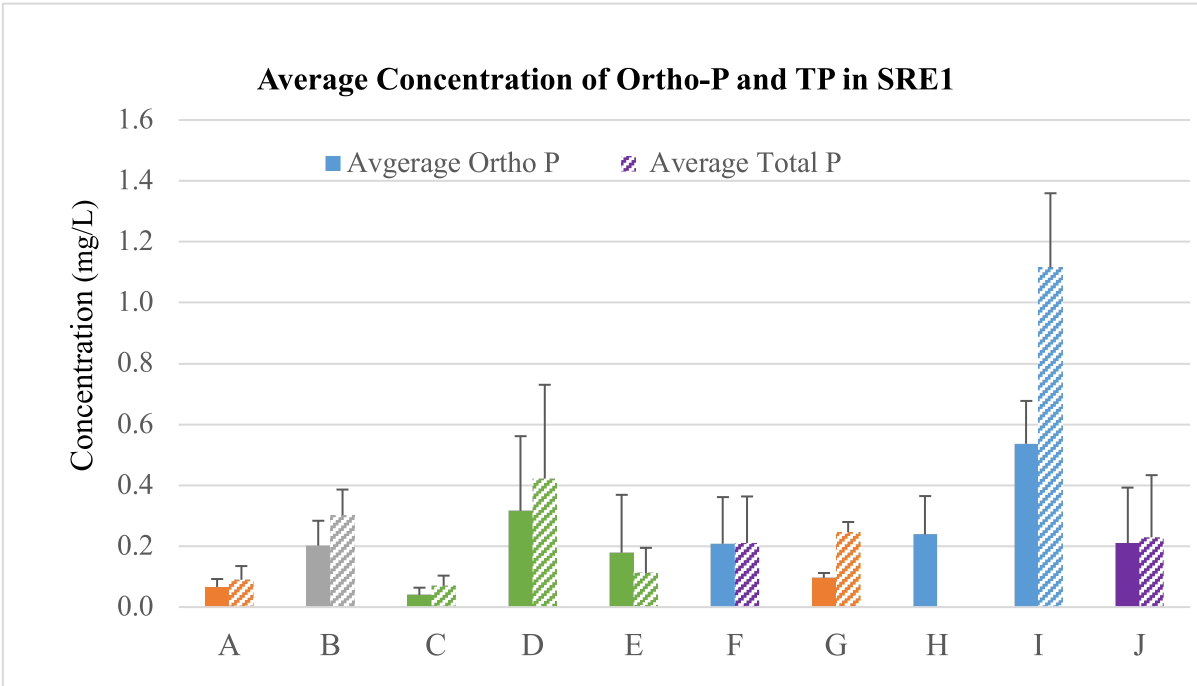


Figure 2.6. Mean concentration of orthophosphate (Ortho P) and total phosphorus (TP) in the first simulated rain event (SRE1) of the column study. Leachate results for SRE1 represent drainage from a 50.8 mm simulated rainfall event (2 in of DI water). Total P results were not calculated for sample H due to sampling errors. Error bars indicate SD.

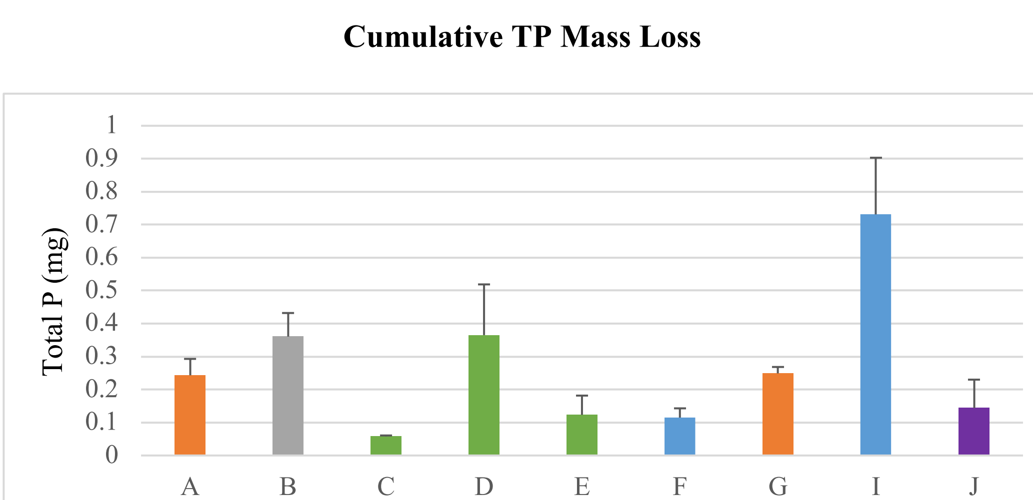


Figure 2.7. Average Column Study cumulative mass loss of total phosphorus (TP).

Higher P losses from samples D and I may be explained by the soil texture i.e., a 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-P 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. However, there was no clear correlation between leachate concentrations and soil P values. Rather, they found that the soil hydrology 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 soil 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 as well as the highest mass losses of TP.

2.4 Conclusions

Together, the interview results along with the analysis of MDOT SHA furnished topsoil tests indicate that agency's effort to increase compost usage by amending the OM specification for furnished topsoil was complicated by a number of unknown factors. More than half of routine topsoil providers suggested that meeting the OM standard through compost addition is burdensome for one reason or another. The fact that the proportion of soil tests that passed the pH standard decreased after 2019 supports concerns that compost usage makes it harder to comply with the MDOT-SHA 2021 standards. Therefore, a broadening of the pH and SS standards could open the door for more compost, or closely associated product, usage.

Soil producers by and large seek and retain topsoil sources for highway projects which do not need alteration. When organic amendment is necessary to comply with furnished topsoil standards, composted yard waste is the preferred amendment. Alternatively, (uncomposted) wood-waste mulch is commonly used to raise the concentration of OM, when leaf compost is not available or too costly. To ensure that the benefits of organic amendments are realized and the targeted adjustments to SHA specifications are met, amendments should be added as close to seeding as possible.

Even though biosolid products are cost effective, widely available, and rich in OM and nutrients, they are avoided due to perceptions that the pH and SS standards for furnished topsoil will not be met after biosolids are incorporated. A lack in understanding of how to properly use and store biosolids by topsoil producers further hinders use. Better guidance could encourage increased use of biosolids, since products derived from biosolids vary greatly in chemical and physical properties, including moisture content (Wang et al., 2008). Furthermore, better guidance could clear up misconceptions about the effects of incorporation on pH, since anaerobically digested biosolids are known to lower soil pH in many cases, not raise it (McIvor et al., 2012; Dede et al., 2017). Other studies, such as one reported by Hosseinpur and Pashamokhtair (2013), validate producers' concerns that biosolids raise the SS concentration of soils since the results showed that biosolids additions significantly increased soil salinity. However, recommendations could address how elevated concentrations of soluble salts in soils could be leached out with suitable pre-treatment techniques or over time, after application. Lastly, guidance could address how the US EPA has sought to reduce regulatory burdens associated with biosolids through the formation of the Class A Exceptional Quality (EQ) designation. Biosolids that meet Class A EQ standards can be applied to land with no restrictions (other than those mandated by individual states). Furthermore, they are exempt from the EPA Part 503 Biosolids Rule general requirements, management practices and site restrictions, which could make biosolids a more desirable soil amendment.

The characterization of the ten furnished topsoil samples emphasizes that it is not possible to make general assumptions about amendment effects on soil properties without a knowledge of incorporation rates and the properties of the base soil type used. Furthermore, 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 are better described than we were able to in this preliminary column study. Nevertheless, a soil TN test and organic carbon test can offer nutrient managers insights to the potential loss of N and P through leaching, which may influence nutrient management decisions. 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 over time. 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 754 $mg \cdot kg^{-1}$ after examining the concentration and spatial distribution of soil TN across various land use areas. For example, the reported soil TN concentration for sample B in this study was nearly three times higher than the average determined by Zhao and Xia (2012) and lost more than 50% N than any other sample. A soil analysis with such a TN result could be used to justify a “wait and see” approach for fertilization for ground cover establishment. With regard to P, the loss of particulate bound-P associated with erosion is the primary concern since P mobility is generally limited in soil. However, sample I from the column study showed that organic-P can leach in concentrations that exceed typical stormwater TP concentrations (0.25 - 0.45 mg-P$\cdot$L^{-1}) seen along highways (Minnesota Stormwater Manual, 2021). Because nitrate and P losses are associated with sandy soils as shown by Djodjic et al. (2004) and Wyatt et al. (2017), limiting the amount of sand in MDOT SHA furnished topsoil could possibly reduce nitrate losses and TP losses in sandy soil with high organic C. Finally, McDowell et al. (2021) concluded that dissolved organic-P should be included in groundwater monitoring programs because dissolved organic-P losses increased relative to ortho-P with depth. Therefore, if state agencies such as MDOT SHA continue to recommend organic amendments as a BMP and/or soil amendment, research into the fate of organic-P should be prioritized. With these recommendations and better guidance, which incorporates ongoing research into soil leachates, N and P losses can be reduced even as compost usage is further expanded along Maryland highways.

Chapter 3: Increasing fertility of highway topsoil with organic waste products and effects on turfgrass establishment and nutrient uptake

3.1 Introduction

3.1.1 Enhancing Roadside Vegetation Establishment with Organic Soil Amendments

Highway construction activities often negatively impact soil quality, which diminish vegetation establishment and coverage (Zhao et al., 2007; Trammell et al., 2011). Increasingly, transportation agencies seek sustainable options for enhancing groundcover along highway embankments to prevent erosion. Incorporating organic amendments into highway topsoil is one such option. Organic matter (OM), a constituent of many urban waste products, such as compost and biosolids, enrich soil by improving physical characteristics such as soil bulk density, porosity, aeration, and water holding capacity, as well as the availability of nutrients by addition, pH improvements, and greater cation exchange capacity (Diacono and Montemurro, 2010; Dunifon et al., 2013; Schmid et al., 2017; Ferreiro et al., 2020). Numerous studies have shown that organic amendments enhance germination and increase coverage of grass 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).

Composts and other organic amendments, such as biosolids enhance the physical properties of soil and add macro- and micro-nutrients. However, nutrient availability varies by product, which requires an understanding of not only nutrient contents but availability. Products that are fully composted generally release nutrients slowly over time, stretching plant benefits over multiple seasons (Sullivan et al., 1998). However, many biosolids provide soluble nutrients, especially nitrate (NO_3^-) and ammonium (NH_4^+) immediately following incorporation (Rigby et al., 2016). Understanding these differences, coupled with proper selection of OM amendments to affect short- and long-term nutrient dynamics could help transportation agencies reduce fertilizer use and maintenance costs.

Plant available nitrogen is a critical factor in the establishment of roadside vegetation (Mola et al., 2011). Balancing near and long-term nitrogen (N) requirements calls for a temporal understanding of how N is released from OM when organic amendments are used. Mineralization is complicated and depends on a multitude of factors including temperature, moisture, time and the carbon: nitrogen (C:N) ratio (Jansson and Persson, 1982). When N is not adequate in OM to meet the needs of a growing population of microbes, it is taken out of the soil solution rendering it temporarily unavailable for plant uptake in a process called immobilization. In time, microbes cycle nutrients, including N, back into soil. Cogger (2005) reviewed soil studies in which compost was used to remediate disturbed urban sites and concluded that a C:N ratio of 20:1 or less provided a ready supply of plant available N. 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 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 with short- and long-term goals as well as the need to provide supplemental N when the ratio is high to facilitate turfgrass establishment.

When using organic nutrient sources, N is usually the primary consideration since it is needed in the greatest amount. Jimenez et al. (2013) showed that early establishment of vegetation on newly constructed road slopes is highly associated with the relationship between vegetation cover, nitrate, and organic matter during the first two years. The amount of N applied at germination will affect the long-term make-up of the roadside plant community as well as the maintenance regiment. Booze-Daniels et al. (2000) recommended applications of <100 kg-N·ha^{-1} to encourage the establishment of legumes in mixed stands with grasses, which reduce long term fertilizer requirements. Dunifon et al. (2013) demonstrated that applying compost at a rate of 213-320 kg-N·ha^{-1} (first year) promoted the growth of broadleaf weeds in addition to the species sown. Highway agencies that want to avoid broadleaf weeds for aesthetics or those that want to establish a low maintenance cover should therefore avoid amendments that release high rates of N in the first year.

An adequate supply of P is also important to ensure vegetative success. Carrow et al. (2001) recommend 49 kg-P_2O·ha^{-1} for turfgrass establishment on soils with sufficient soil P test results or where deficiencies are not expected. Where soil P is unknown or limited, they recommend two applications: 98 kg·ha^{-1} to be mixed into the root zone (up to 10.16 cm) and an additional 49-98 kg·ha^{-1} to be surface applied just prior to or after seeding.

It is widely understood that organic amendments composed primarily of animal wastes, including human, have high concentrations of P. Yet, much of the P in biosolids may be bound to inorganic materials (Fe, Al and Ca) or to soil particles. Phosphorus availability is largely determined by the treatments applied at sewage plants to remove P (McCoy et al., 1986). Regardless, the P:N ratio will determine the amount of OM applied in states with strict P requirements, such as Maryland. Notably, P restrictions are avoided in Maryland when compost amendments (meaning those that are incorporated into soil as opposed to surface applied) are used for turfgrass establishment. In such cases, a thickness of 2.54 cm of compost incorporated into soil is recommended regardless of the source material and its associated chemical properties (Carroll and Turner, 2016).

Generally, fertilizer recommendations are based on the macro-nutrients N, P and K. Potassium is needed in large quantiles compared to P and unlike P, is susceptible to leaching. The addition of OM helps to retain K by increasing the cation exchange capacity (CEC). However, K is usually found in low concentrations in organic amendments as compared to mineral sources (Hue and Silva, 2000). Micronutrients (B, Cu, Fe, Mn, Z) are needed in small quantities but deficiencies can have major impacts on health and growth. Soluble salts (SS) refer to inorganic soluble ions such as Ca^{+2}, Mg^{+2}, Na^{+}, Cl^{-1}, SO_4^{-2} and HCO_3^{-}, and others. Sources include OM and fertilizers (Gondek et al., 2020). Excessive concentrations 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. A buildup of soil OM is associated with improved micronutrient dynamics (Dhaliwal et al., 2019). Several studies conclude that organic amendments make ideal fertilizers for areas with micronutrient deficiencies (Richards et al., 2011a; Zhang et al., 2015; Anees et al., 2016). However, evaluations mostly assess repeated long-term use of organic amendments. Therefore, it is unclear whether a one-time addition to furnished topsoil will significantly improve micronutrient availability over an extended period of time.

3.1.2 MDOT SHA Topsoil Specifications

Topsoil is not suitable for supporting roadway construction. Therefore, it is removed as a first act in the construction process. Occasionally, the removed topsoil is stored in nearby stockpiles until it is reapplied following construction activities. Other times, *furnished topsoil*, defined by MDOT SHA as a natural, friable surface soil that is uniform in color and texture but is not derived from the project, is trucked in from other areas, offsite. Furnished topsoil is subject to the requirements found in MDOT SHA's Standard Specifications for Construction and

Materials manual. As of this writing, the agency imposed the following pH, OM, and SS specifications for furnished topsoil: 6.1 – 7.4; 4 – 8% (by weight); and 500 ppm (0.78 mmhos/cm) or less, respectively. (Note: textural standards were omitted since they are not discussed in this paper.) Concerning SS, electrical conductivity (EC) is used as an indirect measurement to determine compliance with the MDOT SHA standard since EC is positively correlated with the concentration of SS in soil. However, EC does not identify the type of ions present in the sample, which could lead to misplaced concerns if Na^+ and Cl^- concentrations are not disproportionate (Gondek et al., 2020).

With the passage of 2014 HB878 (*State Highway Administration - Compost and Compost-Based Products - Specification*), Maryland legislators aimed to divert organic material from landfills. Legislators also hoped the bill would result in decreased fertilizer use throughout the state. To comply, MDOT SHA incrementally increased the minimum OM standard for furnished topsoil to meet the target goal of 4% by 2019. The agency believed that topsoil dealers would add composts to soil when tests revealed that the concentration of OM fell below the specified minimum. Chapter 2 discussed the effectiveness of the strategy and revealed that the composts most often used by topsoil furnishers to raise the OM content of MDOT SHA topsoil are finely shredded tree mulch and composted yard waste. Even though dealers were not using biosolids in MDOT SHA soil, a biosolids treatment was included in this study since biosolids are commonly used by other transportation agencies and are widely available throughout Maryland.

For clarification, MDOT SHA vaguely defines three categories of compost: *Type A* – composed primarily of biosolids, manure, and similar source materials with low C:N ratios; *Type B* – composed primarily of tree leaves, lawn clippings, and similar source materials with high C:N ratios; and *Type C* – composed primarily of chipped, ground or granulated wood, bark, and similar source materials with very high C:N ratios ("Standard Specifications for Construction and Materials," 2023). The C:N ratios for the categories are not defined. All products used in this study are considered composts by MDOT SHA standards even though they do not fit the definition of compost as described by the US Composting Council.

3.1.3 Research Objectives

The overall objective of this research was to develop a set of recommendations to improve specifications for compost and compost amended topsoil (CAT) to maximize rapid establishment of turf on highway embankments. To accomplish this goal, MDOT SHA specified furnished topsoil was amended with one of the following *specified* composts: biosolids (Type A), composted leaf and yard waste (Type B), or finely ground tree mulch (Type C). Specific objectives included:

- To compare the resulting CATs for differences, if any, in soil fertility before and after a typical establishment period.
- To compare turfgrass establishment (shoot and root growth) to assess the effects of the CATs on vegetation establishment.
- 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 form is presented in Pamuru et al. (in preparation).

3.2 Materials and Methods

3.2.1 Soils and Amendments

Two greenhouse microcosm (tub) studies (TS1) and (TS2) were conducted in the UMD greenhouse complex in College Park, MD. For TS1, the control, an unamended topsoil (CUT1), and two pre-mixed furnished topsoils were sourced from commercial topsoil dealers. (Each dealer was included on the MDOT SHA list of qualified product providers.) The pre-mixed topsoils were amended with either wood mulch (MAT1) or composted leaf/yard waste (LAT1). Although amendments were disclosed, the associated incorporation rates were not due to the difficulty dealers have in tracking specific rates. This is because furnished topsoil properties are fluid depending on the nature of incoming materials, which are mixed into existing stockpiles (Chapter 2). Because a pre-mixed biosolid-amended topsoil (BAT) was not available, we amended the control soil (CUT1) with Fresh Bloom® that was acquired in May 2021 and was stored in sealed plastic containers until it was incorporated into the control soil. Fresh Bloom ® is an EPA Class A EQ biosolids product produced by Blue Plains Advanced Wastewater Treatment Plant (Washington, DC). It is produced through anaerobic digested, which is preceded by thermal hydrolysis. After digestion, the biosolids were dewatered. The incorporation procedure we used for BAT1 and BAT2 is described below.

Although TS1 soils demonstrated the influence of different treatments on 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 used an unamended control soil (CUT2) as the base soil for TS2 amended soils: MAT2, LAT2, and BAT2.

In an effort to formulate an optimal blend that complied with the MDOT SHA OM requirement for furnished topsoil (Chapter 2, Table 2.1), 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 percent OM vs percent addition (by volume) of each organic material to the topsoil plot, to estimate the required percent of organic amendment needed to raise the soil OM to a target value of 6% (Appendix B). The volume of amendment needed for each treatment was: 8% 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 10.16 cm was 38.3 L. Therefore 3.06 L, 2.08 L, and 3.98 L were added to each microcosm for mulch, composted leaf yard waste and biosolids, respectively. Soil and amendments were measured and poured into a wheel barrow on a tub-by-tub basis. Then, soil and amendments were mixed by hand. After materials were thoroughly and evenly mixed, the contents of the wheel barrow were transferred to a prepared tub. Microcosms were randomized by treatment on three benches within the University of Maryland Greenhouse complex. Supplemental fertilizer was not applied. All tub study treatments fell within the MDOT SHA OM specification (4 - 8%), including the control (CUT2).

3.2.2 Tub Study Design

Each microcosm study consisted of sixteen (51 × 74 cm plastic tub) microcosms (4 reps / treatment). The design of the microcosms permitted subsurface leachate and surface runoff volumes to be collected separately (Figure 3.1). 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. A permeable green roof geotextile filter (Standard Duty Separation Fabric, Conservation Technology; Baltimore, MD) held soil within the tubs while allowing water to pass through holes drilled into the bottom of each tub. The geotextile material satisfied the commonly used filter selection criteria (pertaining to retention and anti-clogging standards) such that the hydraulic compatibility between the filter and the overlying soil was not compromised.

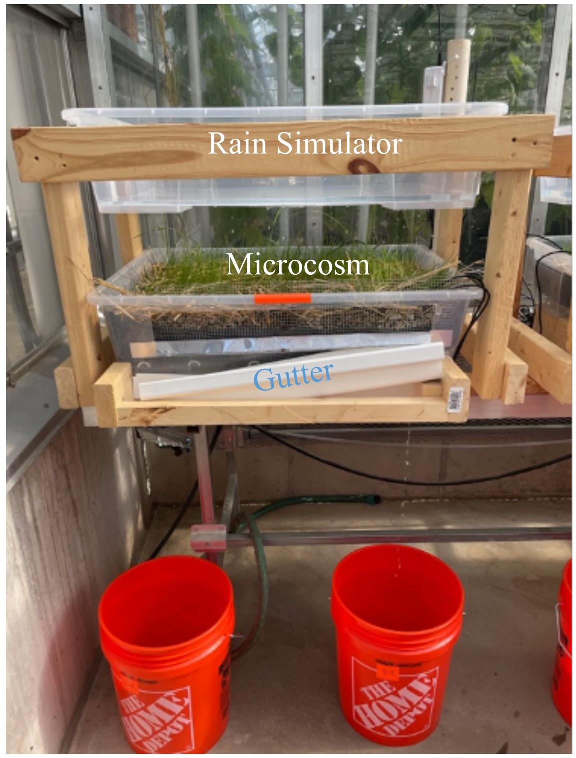


Figure 3.1. Example of a microcosm, removable rain simulator, and bucket collection system for leachate (left) and runoff (right). Gutters channeled runoff (shown) and leachate (hidden behind the runoff gutter) to collection buckets during simulated rain events.

Removable rain simulators (at top of Figure 3.1) were constructed from tubs identical to the microcosm tubs and were suspended approximately 25.4 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. Plastic gutters directed any leachate and surface runoff (when this occurred) to individual clean 22.7 L plastic collection buckets. The depth of soil in each tub was 10.16 cm (4 in). Each tub was seeded with a standard MDOT 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 224 kg·ha^{-1} (8.32 g/tub). After seeding, 1 kg·ha^{-1} of straw was sprinkled over treatment surfaces to mimic MDOT SHA landscaping practices and to help disperse water falling from the rain simulators. TS1 was seeded June 1, 2021 and harvested July 21, 2021 for destructive analyses. TS2 was seeded September 13, 2021 and harvested November 8, 2021.

In both studies, two SREs were applied one week apart before seeding the microcosms. After seeding, weekly SREs continued for the duration of each experiment. The number of SREs for TS1 and TS2 were 8 and 9, respectively. Additionally, 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 SREs equivalent to a 2.54 cm rainstorm (~8,720 mL) were applied to each tub at an approximate rate of 101.6 mm·hr^{-1}. The volume of the leachate collected in each bucket was measured after every SRE. Samples were measured by the UMD Environmental Engineering Laboratory (EEL) for Total N and Total P, in addition to many other measured parameters (Pamuru et al., in preparation) 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.

3.2.3 Soil Analyses

Composite soil samples were collected for TS1. Samples were drawn from each stockpile before soil was loaded into the microcosms. At the conclusion of the project, composite samples were collected by drawing an equal volume of soil from each tub within a treatment (i.e, a pooled sample analysis). To allow for statistical analyses, individual samples were drawn from each replicate tub in TS2. All soil samples used in this study were tested by both the UMD EEL (Appendix C) and Matrix Sciences, Chicago, Il (formerly AgroLab of Harrington, DE). Analyses included: electrical conductivity (EC), pH (1:1), cation exchange capacity (CEC), OM concentration (OM%), total nitrogen (TN), carbon to nitrogen ratio (C:N ratio), total phosphorus (TP), Mehlich-3 P (M3P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na) and manganese (Mn). The following analyses were included in TS2 only: Nitrate-N, Ammonium-N, iron (Fe), aluminum (Al), boron (B), copper (Cu), and sulfur (S). Test methods are identified in Table 3.2. The lab where specific analyses were conducted is identified in the results.

Table 3.1: Summary of soil test methods and references. Boldface type identifies analyses that were included in Tub Study 2 but not Tub Study 1.

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 colorimetry	("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., 2005)
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	Inductively coupled plasma spectroscopy (ICP)	(Mehlich, 1984)

3.2.4 Plant Growth and Nutrient Uptake Analyses

Analysis of Percent Coverage: Turfgrass coverage was quantified 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 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 software (Turf Analyzer, Green Research Services, LLC).

Height and Dry Mass Measurements: TS1 vegetation (both turfgrass and weed biomass) were harvested 7 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, weed shoot biomass was removed by cutting the stem at ground level. Weed shoots were immediately placed in paper bags and dried at 50 °C. After 48 hrs, weed shoot mass was recorded. In contrast, turfgrass shoot biomass was cut at the soil surface. Once harvested, shoots were immediately refrigerated until all microcosms were processed. Then, 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. Debris was removed and the remaining roots were dried and measured in the same manner described for above ground biomass. Turf and weed roots were combined and analyzed together. Procedures for plant growth and tissue analyses were identical for TS2 except were refined 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 Matrix Sciences for analysis of the following: % N, % P, % K, % Ca, % Mg, % S, % Na, Zn (ppm), Fe (ppm), Mn (ppm), Cu (ppm), B (ppm), Mo (ppm). Nitrogen was assessed via combustion (Horneck and Miller, 2019) and the remaining nutrients were assessed using ICP after plant tissue was digested (Huang and Schulte, 1985).

3.2.5 Nutrient Recovery Calculations

Soil, tissue, and leachate TN and TP were recorded for each replicate microcosm in TS2. 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 SREs. These calculations help decipher whether N and P additions were adequate or in excess for turfgrass establishment. They do not reflect actual 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 weight 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 addition of N and P via effluent was calculated by adding the respective weekly concentrations multiplied by the volume of simulated stormwater applied (8,720 mL). Plant uptake was determined by multiplying respective tissue concentrations by the total dry mass of above ground growth.

3.2.6 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 mentioned, treatment means, standard errors (SE), and p-values are listed within the text or the specified table/figure.

3.3 Results and Discussion

3.3.1 Amendment Effects on Furnished Topsoil Standards

Initial and final soil properties are summarized in Tables 3.3 and 3.4. Before leaching and seeding, TS1 and TS2 treatments fell within the specified OM and pH ranges of MDOT SHA furnished topsoil standards: pH (6.1 – 7.4), % OM (4 – 8%), and soluble salt (≤ 0.78 mmhos/cm). However, BAT1, BAT2 and MAT1 samples exceeded the SS limit. Otherwise, all other TS1 and TS2 soils fell below the maximum SS limit. The appropriateness of the MDOT SHA SS standard is confused by published research on the grasses used in the MDOT SHA turfgrass seed mixture. Ali Harivandi et al. (1992) reported general difficulty in establishment and maintenance > 3 mmhos/cm for Kentucky bluegrass and > 6 mmhos/cm for tall fescue. These ranges far exceed MDOT SHA's current limit of 0.78 mmhos/cm. Based on this evidence, it is unlikely that salts restricted growth in the three treatments that exceed the MDOT SHA SS standard. Therefore, this research study along with the available literature justifies consideration for a higher MDOT SHA furnished topsoil SS limit when topsoil is intended for turfgrass establishment.

Concerning pH, post-study pH measurements were higher than pre-study measurements for all soils, except BAT1, across both studies and exceeded the specified range for CUT2, MAT2, and LAT2. Even though the final BAT1 pH result (5.2) was lower than the initial result, it too was outside the specified range (6.1 – 7.4). Nevertheless, the pH range observed between the two tub studies (5.2 to 7.5), was unlikely to restrict turfgrass seedling growth and subsequent establishment of the tall fescue and Kentucky bluegrass seed mixture used in these studies and by MDOT SHA. For instance, Zhang et al. (2012) showed that there was no decline in Kentucky bluegrass quality at a mild (8.0) alkali stress. Additionally, both grasses species used in the studies are tolerant of soil pH < 6.0 (Carrow et al., 2001). These findings coupled with the growth results discussed below support expansion of the MDOT SHA furnished topsoil pH standard to the range observed in these studies: 5.2 to 7.5.

3.3.2 Amendment Effects on Soil Nutrients

Since composite samples were taken for the initial TS1 soil tests, statistical differences could not be determined by treatment (Table 3.3). Even so, the results help to dissuade concerns about the effects of BAT on pH and SS because results outside the specified ranges did not restrict growth as compared to other treatments (discussed below). Furthermore, TS1 soil test results along with growth measurements and tissue test results show strong evidence that biosolids increased both TN and plant available N (PAN). Soil N was nearly 2× higher in BAT1 as compared to LAT1, which was notably higher than CUT1. Additionally, combined results highlight the importance of the C:N ratio on establishment and growth since high ratios (>20:1) can immobilize PAN (Cogger, 2005). The respective initial C:N ratios for CUT1 and MAT1 were 25:1 and 19:1, which were higher than the LAT1 and BAT1 ratios.

Table 3.2: Tub Study 1 initial and final soil fertility summary. Treatments included an unamended topsoil (CUT1), a soil amended with finely shredded tree mulch (MAT1), a soil amended with composted yard waste (LAT1), and a soil amended with biosolids (BAT1). Sufficiency (Suf.) ranges for OM, EC, and pH 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.

		CUT1		**MAT1**		**LAT1**		**BAT1**	
		Sandy Loam		Sandy Loam		Silt Loam		Sandy Loam	
Measurement	**Suf. Range**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**
OM%	4-8	7.2	6.4	6.32	5.86	6.03	6.25	5.76	6.56
EC (mmho/cm)	≤ 0.78	0.59	0.3	**1.37**	**0.79**	0.80	0.47	**2.16**	**0.94**
pH (1:1)	6.1–7.4	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
TC ($mg \cdot kg^{-1}$)		31,980	29,774	30,215	24,402	29,000	31,049	26,662	29,257
TN ($mg \cdot kg^{-1}$)		1242	1687	1628	1501	1958	1875	3956	3661
C:N		25:1	18:1	19:1	16:1	15:1	17:1	7:1	8:1
Total P ($mg \cdot kg^{-1}$)*		435	297	438	587	370	358	1414	2420
M3P ($mg \cdot kg^{-1}$)*	27-55	**26**	**23**	**15**	**17**	**20**	**26**	92	146
K ($mg \cdot kg^{-1}$)*	50–116	137	139	158	140	126	142	188	174
Ca ($mg \cdot kg^{-1}$)*	375-750	1834	1818	2171	1843	1993	2145	1311	1341
Mg ($mg \cdot kg^{-1}$)*		153	143	126	111	378	386	181	200
Na ($mg \cdot kg^{-1}$)*		26	35	19	28	23	38	23	40

* Determined by Matrix Sciences, Inc. Other analyses were completed by the University of Maryland Environmental Engineering Lab.

Mehlich-3 P is widely used in the Mid-Atlantic as an agronomic soil test for P (Sims et al., 2002). Like N, it is notable how much greater extractable P (M3P) and Total P in BAT1 was compared to the other treatments, which were similar. BAT1 M3P and TP were > 3× higher than any other treatment at the beginning of the study. It should be noted that P was present in the tap water used in the projected. Therefore, approximately 22 mg of P was added over the course of the TS1 SREs. However, the gains in total soil P for MAT1 and BAT1 from the beginning of the experiment to the end were greater than the addition of P from the tap water and are better explained by the sampling technique (composite samples) and the heterogeneous nature of furnished soil. Regardless, TS1 soils provide evidence that amending furnished topsoil with organic materials supplies needed nutrients. However, TS2 provides a clearer picture of the effects of mulch, composted yard waste and biosolids on furnished soil (Table 3.4).

Table 3.3: Tub Study 2 initial (I) and final (F) soil fertility summary. Treatments included an unamended topsoil (CUT2) and a soil amended with either finely shredded tree mulch (MAT2), composted yard waste (LAT2), or biosolids (BAT2). Analyses are expressed as mean ± the SE. 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 between treatments. Values in rows with different letters are significantly different (α = 0.05). Results for nutrients are reported in $mg \cdot kg^{-1}$.

Analysis*	Suf. Range	Time	CUT2	MAT2	LAT2	BAT2	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±0.05	5.41±0.12	5.06±0.13	5.1±0.18	
pH*	6.1 – 7.4	I	7.21±0.01[b]	7.31±0.01[c]	7.18±0.02[b]	6.79±0.02[a]	<0.001
		F	**7.55±0.02**	**7.52±0.01**	**7.55±0.01**	7.21±0.03	
EC* mm hos/cm	≤ 0.78	I	0.3±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/100g		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	1,386±12[a]	1,460±35[ab]	2,223±125[b]	2,934±46[c]	<0.001[‡]
		F	1,394±58[a]	1,664±74[b]	1,908±58[b]	2,553±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	1.15±0.4^{a}	0.9±0.3^{a}	0.9±0.4^{a}	88±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}	1,394±78^{b}	<0.001
		F	506±22^{a}	500±4^{a}	570±17^{a}	1,357±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	122±2.9	176±1.8	85±6.0	
Ca	375 – 750	I	2,329±59^{a}	2,621±77^{ab}	3,026±73^{b}	2,690±213^{ab}	0.014
		F	1,950±64	2,150±64	2,150±50	2,400±147	
Mg		I	126±3^{a}	147±3^{b}	213±3^{c}	142±5^{b}	<0.001
		F	111±2	130± 3	152±2.4	134±3.5	
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}	34062^{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±0.09^{a}	3.1±0.05^{a}	3.2±0.05^{a}	4.00±0.18^{b}	<0.001
		F	2.6±0.05	2.5±0.02	2.7±0.08	4.9±0.4	
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±3.3**	**10±1.0**	**12±1.2**	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.

TS2 results (Table 3.4) show that composted yard waste and biosolids significantly increased the availability of soluble N, P and K. Specifically, LAT2 had twice as much nitrate than CUT2 while BAT2 had 4× more nitrate. Additionally, BAT2 initially had nearly 87 mg·kg^{-1} more ammonium than CUT2. While TP was not significantly greater in LAT2 than CUT2, M3P was; but it was not sustained. However, the increase was low in comparison to the increase seen in the BAT2 TP result. Potassium concentrations were also significantly raised in LAT2 and

BAT2 by amendment additions. On the other hand, neither PAN, M3P, or K was greater in MAT2 than CUT2.

Another noteworthy difference in soil fertility is highlighted by the results for sulfate (SO_4^{2}-S). Amending the control soil with mulch and composted yard waste did not significantly alter the CUT2 SO_4^{2}-S concentration, which was near the upper limit of the recommended sufficiency range of 40 ppm (Carrow et al., 2001). On the other hand, biosolids raised the SO_4^{2}-S concentration to 149 ppm. It remained above the sufficiency range after growth and leaching while the other treatments fell below sufficiency ranges.

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 summarized in Table 3.5 will be discussed in relation to the plant tissue analyses and growth measurements in the following sections.

Table 3.4: Tub Study 1 (TS1) and Tub Study 2 (TS2) summary of fertility concerns for control soils (CUT1 and CUT2), and soils amended with the following: finely shredded wood mulch (MAT1 and MAT2), composted yard waste (LAT1 and LAT2), and biosolids (BAT1 and BAT2).

TS1		**TS2**	
CUT1	High C:N, low P	CUT2	High pH, low P
MAT1	High C:N, low P	MAT2	High pH, high C:N, low P, low S
LAT1	Low P	LAT2	High pH, low P, low S
BAT1	None	BAT2	High EC

3.3.3 Amendment Effects on Turfgrass Growth Measurements and Percent 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

(Figure 3.2). The overall difference is attributed to the milder fall temperatures preferred by the cool season grass mix used in both studies.

Figure 3.2a TS1 Turfgrass Coverage

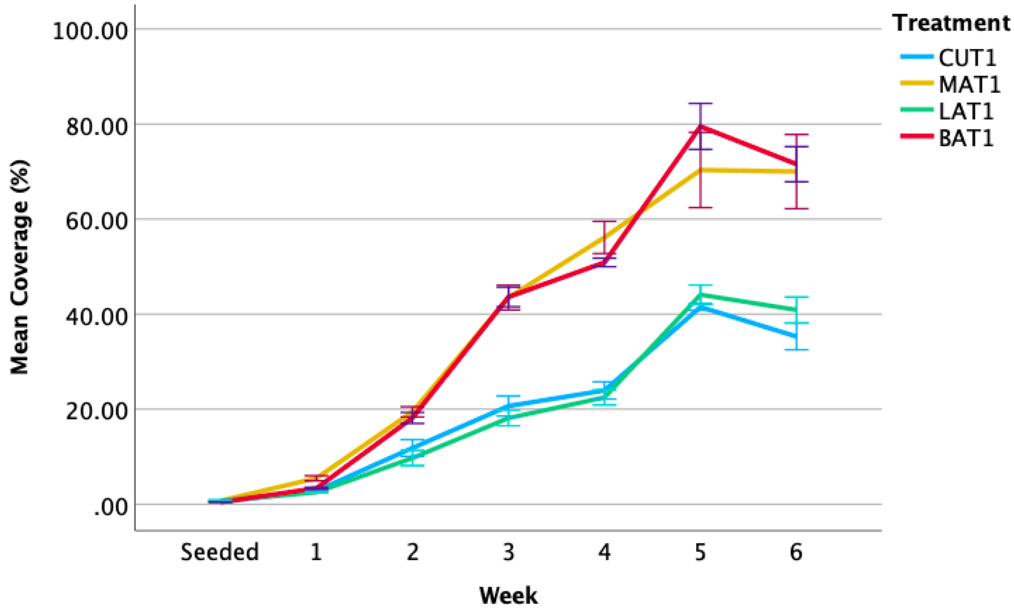


Figure 3.2b TS2 Turfgrass Coverage

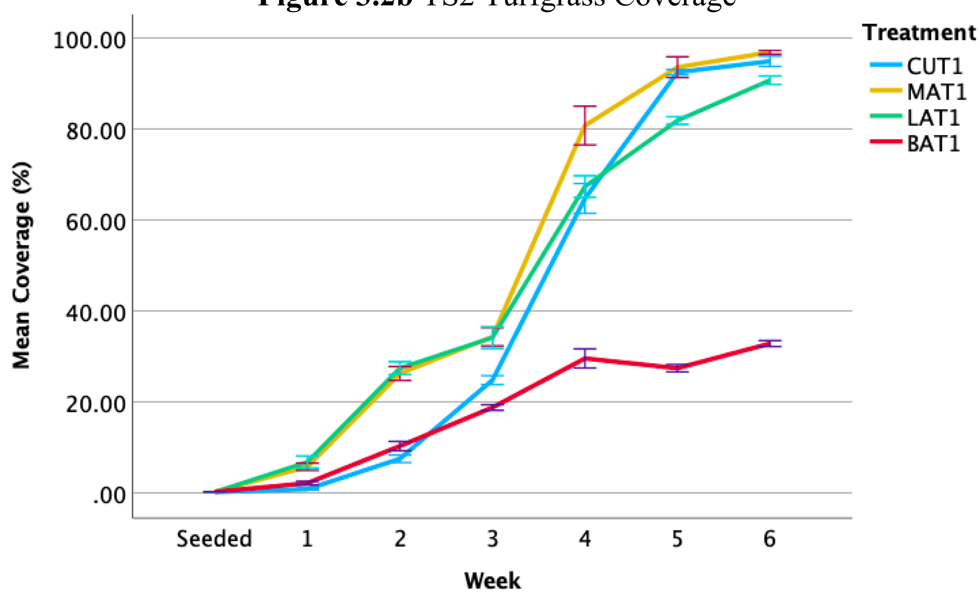


Figure 3.2. Turfgrass percent coverage for Tub Study 1 (TS1) and Tub Study 2 (TS2). TS1 was seeded on 6/1/21 and TS2 was seeded on 9/13/21. Error bars represent SE.

3.3.3.1 Percent coverage for TS1

Final turfgrass coverage was significantly less in CUT1 and MAT1 than LAT1 and BAT1 microcosms (Figure 3.2a). Together with the rate of growth, these results are best explained by soil C:N ratios. The median C:N ratio is typically 12:1 for an Ap horizon (Weil and Brady, 2017). Ratios for CUT1 and MAT1 were 25:1 and 19:1, respectively. When available N present in the soil is inadequate to satisfy both soil microbial and plant uptake needs, plant growth is reduced and the decay of organic materials can be delayed (Hadas et al., 1992). Coverage must exceed 95% to qualify for final acceptance according to MDOT SHA's standards. Mean final coverage did not exceed 95% for any treatment at any time during TS1. The evaluation of TS1 % coverage indicates that attempts to establish standard cool season grasses during the summer in the Mid-Atlantic region are susceptible to failure to meet MDOT SHA's final coverage standard regardless of which amendment is used.

3.3.3.2 Percent coverage for TS2**:**

Overall, % coverage and the rate of coverage was improved in the second study. Within 4 weeks, three treatments achieved over 60% coverage. By week 6, mean turfgrass coverage was ≥ 90% for the CUT2 treatment and ≥ 95% in replicates receiving the LAT2 and BAT2 treatments (Figure 3.2b). Mean coverage for the MAT2 treatment was 32.8%, which was significantly lower than all other treatment averages. Beyond seasonal temperature differences, the improved % coverage and rate of coverage for the CUT2 treatment as opposed to CUT1 treatment could be explained by the soil properties, which differed because CUT1 soil was not acquired from the same dealers as CUT2 soil. Of particular note is the difference in the C:N ratios, which were 25:1 for CUT1 and 11:1 CUT2. Despite the improved results for CUT2, coverage still fell below the 95% threshold required by SHA.

3.3.3.3 Growth Measurements**:**

The mean turfgrass height for all treatments across both tub studies (Table 3.6) exceeded the 10.2 cm (4 in) minimum required for MDOT SHA final approval. Under ideal temperatures, mean height for MAT2 was only 10.8 cm, statistically less than all other TS2 treatments. Mean height for the remaining TS2 treatments was > 20.7 cm. LAT2 and BAT2 were significantly greater than CUT2 and MAT2, implying that using composted yard waste or biosolids could result in more frequent mowing if used.

Table 3.5: 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). Results are expressed as mean ± the SE. ANOVA was performed to determine if significant differences existed between treatments. Values in rows which have different letters are significantly different (α = 0.05).

		CUT	**MAT**	**LAT**	**BAT**	**P-Value**
Final % Cover	TS1*	35.3±2.8a	40.9±2.7a	70.0±7.8b	71.6±3.7b	<0.001
	TS2	90.7±0.9b	32.8±0.6a	96.9±0.4c	94.9±1.15bc	<0.001
Height (cm)	TS1	11.1±0.3a	12.5±0.6ab	16.55±0.9b	20.8±0.2c	<0.001
	TS2	20.7±0.4b	10.8±0.7a	26.6±1.9bc	31.6±.9c	<0.001
Shoot Dry Mass (g)	TS1	5.6±0.7a	8.15±1.1a	18.0±1.35b	24.15±1.6b	<0.001
	TS2	24±1.8b	7.47±1.0a	39.4±1.6c	67.7±3.65d	<0.001
Root Dry Mass† (g)	TS1*	0.47±0.16	0.41±0.08	0.53±0.02	0.40±0.02	0.396
	TS2	0.94±0.03b	0.33±0.06a	0.85±0.12b	0.58±0.09ab	0.002
Root-Shoot Ratio	TS1	2.59±0.63b	1.77±0.26ab	1.09±0.13a	0.60±0.0.07a	0.009
	TS2	1.45±0.18b	1.55±0.18b	0.79±0.14a	0.30±0.03a	<0.001

† *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.*

* Includes weed biomass

Mean shoot dry mass (SDM) in TS1 included weed biomass and was significantly higher for LAT1 and BAT1 as compared to CUT1 and MAT1. The mean SDM in TS2 was significantly different across all treatments where MAT2 < CUT2 < LAT2 < BAT2. The mean root dry mass (RDM) in TS1 was not statistically different among treatments. However, differences were seen in TS2, where MAT2 RDM was statistically lower than CUT2 and LAT2, while BAT2 was similar to all. When evaluating root: shoot ratios (R:S), LAT and BAT were lower than CUT across both studies, while MAT was similar.

Root:shoot ratio differences can be rationalized by the plant-available N results. Turfgrasses respond to high nitrate levels by diverting carbohydrates to amino acid production instead of storage (in the form of sugars) in roots (Carrow et al., 2001). The result is shoot growth instead of root growth, especially during the summer months for cool season grasses. This explains why the BAT root dry mass 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. Therefore, applications of amendments that exceed N requirements for turfgrass should be avoided, to encourage healthy root development.

3.3.4 Plant Tissue Analysis

Overall, nutrient deficiencies were more prevalent in TS2 than in TS1 (Table 3.7). Shoot N was sufficient and statistically highest for BAT (> 4.5%) in both studies. Otherwise, N deficiencies, as described by Mills and Jones (1996), were significant in all other treatments, ranging between 1.6% and 2.0%. Shoot P was 0.26% and 0.24%, respectively, for TS1 and TS2 BAT treatments. All treatments resulted in P tissue deficiencies, except CUT1, which had a shoot concentration of 0.36%. Phosphorus deficiencies included BAT treatments despite them having statistically higher shoot P concentrations.

The wastewater treatment plant that produces Bloom® reports use of iron salts (ferrous sulfate), liquid alum and lime during the wastewater treatment process ("Blue Plains NPDES Factsheet," 2017). As a result, available P in BAT is bound to Fe, Al, and Ca as inorganic phosphates, which are not plant available (Badzmierowski and Evanylo, 2018). This helps explain why BAT treatments resulted in P tissue deficiencies despite high initial M3P values. Similar results were reported by O'Connor et al. (2004) and Boen and Haraldsen (2011).

Table 3 6: Summary of turfgrass tissue nutrient concentrations for Tub Study 1 (TS1) and Tub Study 2 (TS2). 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 SE. ANOVA was performed to determine if significant differences existed between treatments. Values in rows which have different letters are significantly different ($\alpha = 0.05$).

Nutrient	Suf. Range	Study	Control	Mulch	Leaf	Biosolids	P Value*
N (%)	3.4 – 4.65	TS1	**1.8±0.05ab**	**2.0±0.05b**	**1.6±0.05a**	4.7±0.05c	<0.001
		TS2	**1.47±0.06a**	**1.29±0.03a**	**1.92±0.18a**	4.51±0.11b	<0.001
P (%)	0.34 - 0.50	TS1	0.36±0.02c	**0.23±0.01b**	**0.15±0.00a**	**0.26±0.00bc**	<0.001
		TS2	**0.12±0.00a**	**0.15±0.00b**	**0.15±0.01ab**	**0.24±0.01c**	<0.001
K (%)	3.00 – 4.00	TS1	3.13±0.02	4.00±0.01	4.21±0.07	5.07±0.26	NA
		TS2	3.18±0.10	**2.79±0.10**	4.03±0.22	4.51±0.10	NA
Ca (%)	0.40 -0.45	TS1	0.92±0.02	1.15±0.10	0.70±0.01	1.06±0.01	NA
		TS2	0.82±0.05	1.00±0.06	0.85±0.17	1.09±0.12	NA
Mg (%)	0.24 - 0.29	TS1	0.62±0.02	0.53±0.02	0.48±0.01	0.42±0.00	NA
		TS2	0.37±0.01	0.39±0.01	0.39±0.01	0.48±0.01	NA
S (%)	0.40 - 0.44	TS1	**0.32±0.02**	**0.32±0.01**	**0.22±0.00**	**0.27±0.00**	NA
		TS2	**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	TS1	134±2bc	396±124c	164±24c	93±5a	0.02
		TS2	280±63	389±64	207±20	241±22	NA
Mn ($mg \cdot kg^{-1}$)	54 -74	TS1	99±3	146±7	73±6	290±3	NA
		TS2	73±4	106±5	65±6	71±3	NA
Cu ($mg \cdot kg^{-1}$)	9 - 15	TS1	9±0	11±0	9±0	12±0	NA
		TS2	**6±0a**	**6±0a**	**7±1a**	13±0b	<0.001
Zn ($mg \cdot kg^{-1}$)	28 - 64	TS1	43±3	34±1	28±0	72±6	NA
		TS2	**20±0a**	30±1b	**26±2ab**	41±1c	<0.001
B ($mg \cdot kg^{-1}$)	15 -20	TS1	**11±0**	**11±0**	17±0	**9±0**	NA
		TS2	**5±0.4ab**	**6±0b**	**4.75±0.2a**	**4.25±0.2a**	0.004

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

Shoot S concentrations were low in TS1 and TS2 treatments, resulting in S deficiencies for each treatment across both studies. Even though LAT2 (0.20%) and BAT2 (0.28%) had higher shoot S concentrations than CUT2 (0.16%) and MAT2 (0.15%), concentrations were still well below the typical range for tall fescue (0.40% - 0.44%) as described by Mills and Jones (1996). The soil concentration of SO_4^{2}-S, the direct S source for plants, was significantly higher in BAT2 than other soils and may explain why turfgrass from this treatment had the highest concentration of 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). Furthermore, Biederbeck (1978) explained that total soil S is significantly correlated with soil organic C and TN, which were significantly higher in BAT2 than the control. Keeping in mind that the tub studies were short in duration (8 – 9 weeks), these results along with previous findings suggest that biosolids could be a long-term source of plant available S. This conclusion is upheld by other researchers who demonstrated that (uncomposted) biosolids can be used as a N and S fertilizer (Gilmour et al., 2003; Seth et al., 2006; Boen and Haraldsen, 2011; Moore, 2022).

3.3.5 Nitrogen and Phosphorus Uptake

The amount of N and P taken up by turfgrass was calculated by multiplying the tissue concentrations by the corresponding dry mass (Figs. 3.3a-3.3d). This normalization of tissue contents is important as growth differences significantly affect elemental tissue concentrations, which can confound any results (Lea-Cox et al., 2001; Ristvey et al., 2007). Nitrogen and P uptake was overall greater for TS2 than TS1, because of greater biomass accumulation. Relating differences in TS1 N and P uptake to amendments is not practical since the base soils used were different. However, this issue was corrected for TS2 and thus we can be certain of these treatment differences. Despite this, the pattern for N and P uptake was the same in both studies, where BAT2 > LAT2 > CUT2 > MAT2.

In both studies, BAT shoot growth, and subsequent N uptake, exceeded the other treatments. This is best explained by soil N concentrations which were highest in BAT treatments while the C:N ratios were the lowest. The combination of these factors likely allowed for N mineralization as the experiment progressed, thereby replacing N that was taken up by the turfgrass, lost to the atmosphere, or leached. 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. Mean N uptake was > 6× higher in BAT1 and 4× higher in BAT2 as opposed to other TS1 and TS2 treatments, (Figs. 3.3a and 3.3b, respectively).

Similar to the N results, mean shoot P uptake was significantly greater from BAT than all other treatments in both studies (Figs. 3.3c and 3.3d). This can be explained by significantly higher M3P values that were noted in the final soil measurements, as compared to the other amended soils. Even so, tissue analyses indicated that BAT2 turfgrass was deficient in P, which suggests that had more of the TP in BAT been phytoavailable, P uptake would likely have been greater.

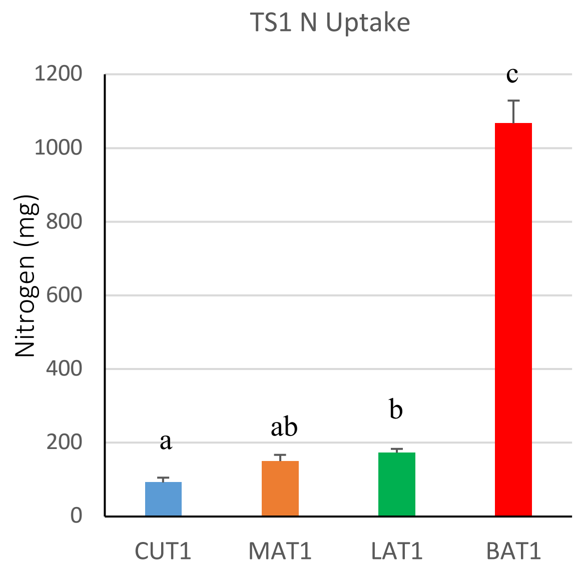


Figure 3.3a
($p < 0.001$)

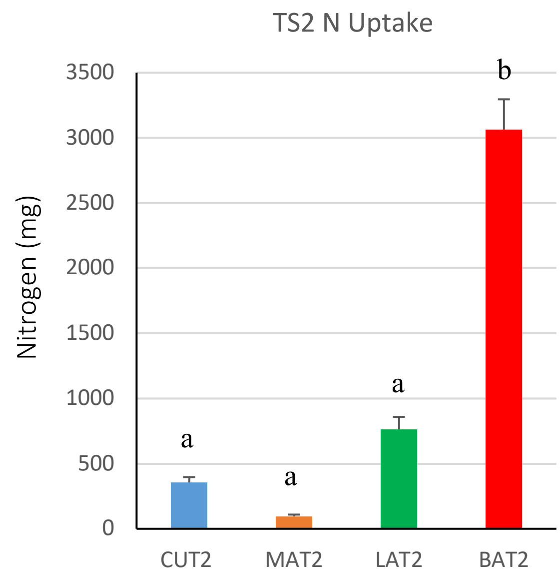


Figure 3.3b
($p < 0.001$)

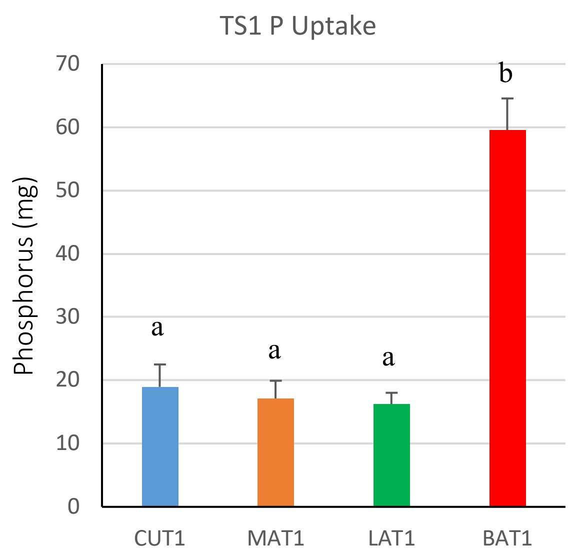


Figure 3.3c
($p < 0.01$)

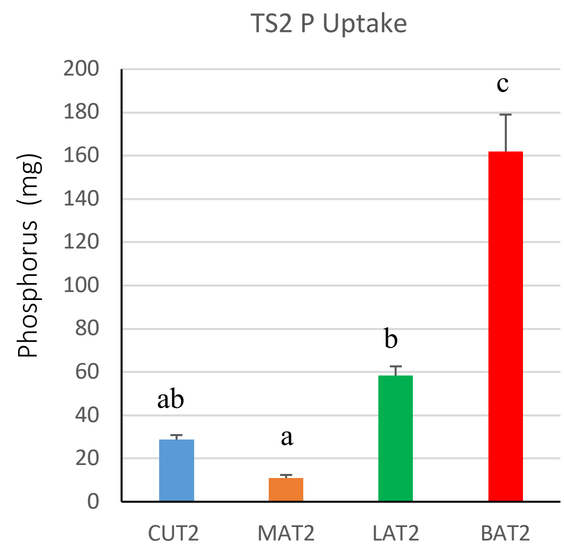


Figure 3.3d
($p < 0.001$)

Figure 3.3. Nitrogen (N) and phosphorus (P) uptake from Tub Study 1 (TS1) and Tub Study 2 (TS2). Bars with different letters are statistically different ($\alpha = 0.05$). Error bars represent SE.

3.3.6 TS2 Nutrient Recovery Calculations

Similar to the N and P tissue uptake calculations, the normalized leachate N and P content (Pamuru et al., in preparation) was calculated (volume × concentration) so that uptake could be compared to leachate losses during the second study (Tables 3.8 and 3.9, respectively). The average monthly cumulative rainfall for the months roughly coinciding with the TS2 timeframe (Sept and Oct) 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$\cdot$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 MAT2 soil N concentration was higher than the initial concentration by approximately 10.7 g. More N (53% - 74%) was removed from the soil through leaching than was assimilated into plant biomass for each treatment, including CUT2.

The pattern of N uptake and leaching was reflective of TN soil contents and N availability (Table 3.8), which was highest from BAT2 > LAT2 > CUT2 > MAT2. Even though MAT2 had a statistically similar concentration of soil TN than CUT2, less N was leached or assimilated, which can be explained by N immobilization caused by the high C:N ratio of MAT2. The addition of biosolids resulted in 10× greater N leaching from BAT2 than CUT2 (Pamuru et al., preparation). The next highest loss came from LAT2, which was 1.7× greater than CUT2. The difference between N uptake and leaching was greatest from BAT2 (2.7 g), lowest from MAT2 (0.07 g) and similar for CUT2 and LAT2 (0.24 g and 0.27 g, respectively). Ideally, the amount taken up is greater than the amount leached to reduce N pollution, but this is difficult. These results considered alongside growth measurements suggest that the amount of biosolids used in this experiment to raise the soil OM content by approximately 20% was far in excess of plant N requirements, and could result in significant N leaching if biosolids amendments were applied to a construction site at this rate.

Table 3.7: Soil nitrogen (g) before and after 228.6 cm of simulated rainfall were applied to Tub Study 2 microcosms, which included a control soil (CUT2) and soil amended with either finely shredded wood mulch (MAT2), composted leaf yard waste (LAT2) or biosolids (BAT2). 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 ± SD Leachate data provided by Pamuru et al. (in preparation).

Treatment	Soil N Start (g)	Soil N End (g)	Soil Difference (g)	N Leached (g)	N Uptake (g)
CUT2	64.5±0.95	64.9±6.26	-0.3	0.60±0.09	0.36±0.08
MAT2	76.8±3.18	87.5±10.04	-10.7	0.17±0.02	0.10±0.03
LAT2	103.1±10.21	89.1±8.70	14.1	1.03±0.09	0.76±0.19
BAT2	136.6±3.40	118.9±13.64	17.8	5.76±0.22	3.06±0.47

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 3.9). In each case, P uptake was greater than P leached. The ratios for uptake:leached were nearly 4:1, 2:1, 9:1, and 31:1 for CUT2, MAT2, LAT2, and BAT2, respectively. Furthermore, CUT2 and LAT2 leached approximately the same mass, meaning the addition of the composted yard waste did not significantly increase P loading to leachate. MAT2 and BAT2, retained more P than the other treatments in terms of leaching. Lower P mobility in MAT could be explained higher soil pH (Penn and Camberato, 2019), while wastewater treatment additives intended to capture P could explain the stability of P in BAT. This means that the amendments used in TS2 to raise the concentration of OM by approximately 20% 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. 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).

Table 3.8: Soil phosphorus (g) before and after 228.6 mm of simulated rainfall was applied to Tub Study 2 microcosms. Treatments included a control soil (CUT2) and soil amended with either finely shredded wood mulch (MAT2), composted leaf yard waste (LAT2) or biosolids (BAT2). Soil before and after results were not significantly different as reflected by the associated test statistics and p-values ($\alpha = 0.05$). 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 ± SE. 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 ($\alpha = 0.05$; $p < 0.001$). Leachate data provided by Pamuru et al. (in preparation).

Treatment	Soil P Before (g)	Soil P After (g)	Soil Difference (g)	Soil t-test *p*-value	P Leached (mg)	P Uptake (mg)
CUT2	24.67±0.9	23.61±1.0	1.06±0.9	0.325	7.74±0.48b	28.77±2.05ab
MAT2	28.22±0.9	26.34±0.22	1.88+0.8	0.104	4.34±0.24a	10.98±1.41a
LAT2	28.36±1.8	26.48±0.8	1.87±2.2	0.479	6.78±0.40b	58.27±4.32b
BAT2	64.90±3.6	63.18±6.9	1.72±9.6	0.869	5.16±0.11a	161.9±17.02c

3.4 Treatment Summaries

3.4.1 Control treatments

Tissue analyses revealed N deficiencies 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. CUT1 mean root dry mass was the second highest despite having the lowest shoot dry mass. This resulted in a high R:S ratio (2.59) as compared to MAT1, LAT1, and BAT1, which were 1.77, 1.09 and 0.6, respectively. Although nitrate and ammonium concentrations were not analyzed in the first study, TS1 root growth supports the theory that plant available N was limited. Carrow et al. (2001) reported that turfgrass root growth rate is highest at low to medium N sufficiency levels and drops dramatically above a medium sufficiency level.

A N deficiency was 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. The analysis of TS2 plant tissue revealed several nutrient deficiencies in CUT2 leaves. A P deficiency was the only deficiency identified by both the initial CUT2 soil analysis and tissue analysis. A comparison of the mean before (40 ppm) and after (17 ppm) CUT2 soil analyses highlighted a sharp drop in S, which showed up as a deficiency in the CUT2 tissue analysis. Sulfur deficiencies are associated with soils that are: heavily leached, sandy or do not receive atmospheric sulfur (Carrow et al., 2001); CUT2 met all criteria. Deficiencies in Cu, Zn, and B are associated with alkaline soils (pH > 7), such as CUT2 (Carrow et al., 2001). Despite these deficiencies, CUT2 establishment rates were better than CUT1 rates, which is attributed to cooler temperatures during fall and a lower C:N ratio. Even so, the above ground growth of the control treatments greatly underperformed compared to other treatments, differences that are largely attributed to low soluble N at the beginning of the study and a soil P deficiency.

3.4.2 Mulch-Amended treatments:

The MAT1 weekly percent coverage, height, and SDM was comparable to CUT1. Like CUT1, the C:N ratio (19:1) was higher than the typical mean (12:1) for cultivated surface horizons, which likely limited plant-available N. Although PAN was not tested in TS1, TN was higher in MAT1 soil than CUT1 at the beginning of the experiment. Additionally, a lower R:S ratio indicates that PAN could have been higher in MAT1 than CUT1. MAT1 had a N deficiency as determined by the tissue analysis and a P deficiency as determined by the soil and tissue analyses; therefore, N and P were the limiting factors for MAT1.

The incorporation of mulch to the base soil in MAT2 increased the C:N ratio from 11:1 in the base soil to 20:1 - higher than the mean of typical surface soil horizons. MAT2 soil was also deficient in P at the beginning and end of TS2. Low N and P availability are again likely responsible for poor turfgrass established in MAT2 microcosms as determined by growth measurements. Nitrogen and P deficiencies were confirmed by the tissue analysis as well as S and Cu deficiencies. The addition of mulch did not alleviate S and Cu deficiencies present in the base soil. The overall evaluation of TS1 and TS2 soil, growth, and tissue measurements indicates that mulch should not be used to raise the concentration of OM without providing a source of P (if planting in a P deficient soil) and N to compensate for N immobilization.

3.4.3 Leaf-Amended 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. Growth measurements followed suit. Overall LAT2 soil fertility was improved by the compost addition, most notably in regards to the primary macronutrients (N, P, and K). Additionally, an ideal C:N ratio was maintained (12:1). Althought, LAT2 supplied more extractable P than CUT2 and MAT2, it wasn’t enough to alleviated a P deficiency in the tissues of turfgrass associated with the LAT2 treatment. Still, LAT improved turf establishment without causing concern that nutrient additions were excessive in terms of N and P leaching losses (Pamuru et al, in preparation

3.4.4 Biosolids-Amended treatments:

BAT1 and BAT2 had the lowest C:N ratios, lowest pH values, highest SS concentrations (above MDOT SHA specifications) and were the only treatments that did not result in leaf tissue N deficiencies. BAT1 had the highest percentage coverage, height, rate of growth and final SDM in TS1, likely due to N availability. In TS2, BAT2 and LAT2 turfgrass coverage and height were statistically similar while BAT2 SDM was greater. Low RDM and high SDM, especially in TS2, are likely explained by excess PAN. The limiting factor for BAT1 and BAT2 growth was most likely P, as indicated by the tissue analyses. Even so, growth was not noticeably inhibited by P availability or SS concentration as compared to the other treatments. Additionally, three of the six nutrient deficiencies observed by the analysis of CUT2 tissue were not seen in BAT2 tissue. Although the concentrations of P and S in tissue associated with the BAT2 treatment were considered insufficient, they were higher than the other treatments, demonstrating that biosolids are a source of plant available P and S. Biosolids haven been shown to be a viable alternative to synthetic fertilizers when soil has multiple deficiencies, especially micronutrient deficiencies, since all nutrients are present (Richards et al., 2011b; Badzmierowski and Evanylo, 2018). However, the rate of N uptake compared to N leaching seen in TS2 indicates that biosolids should not be applied to raise soil OM by 20%. Instead, biosolids should be treated like a N fertilizer and applied at the agronomic rate for turfgrass establishment when used on construction sites to prevent unnecessary N pollution.

3.4 Conclusions

Organic amendments have varied chemical properties and their effects on fertility and turfgrass establishment are highly dependent on the characteristics of the base soil type used. The primary objective for a highway embankment topsoil layer is to provide a hospitable environment for turfgrass establishment. Therefore, base soils should be tested for pH, SS content, C:N ratio, as well as P and N concentrations (as discussed in Chapter 2) to determine which amendment may be best for meeting turfgrass fertility requirements while minimizing nutrient pollution. This study, in particular TS2, demonstrated that LAT is a good source of N, P and K. Additionally, LAT maintained satisfactory pH, SS concentrations, and C:N ratios, which enhanced turfgrass establishment and growth without heavy N and P leachate losses. However, soils with low PAN and/or P deficiencies, such as the base soil used in TS2 may require additional nutrient sources to meet plant nutritional needs. Regardless, amending highway topsoil with composted yard waste could increase local compost usage while reducing overall fertilizer needs.

Caution is advised when applying finely ground wood mulch or biosolids as soil amendments for highway embankment topsoil. While wood mulch raised TN and TP, the immobilization of PAN and extractable P resulted in a significant reduction in turfgrass growth and a failure to meet agency requirements (percent coverage) for final approval. Immobilization of N by MAT was caused by high C:N ratios (~20:1). In time, nutrients held by mulch will mineralize - though likely not in time to aid initial vegetation establishment. It is reasonable to expect that mulch will remain a popular soil amendment on MDOT SHA sites because mulch is a convenient source of OM for suppliers who often sell topsoil as well as mulch products (Chapter 2). In order to prevent nutrient deficiencies, measures, such as a requirement for dealers/landscapers to self-report amendment additions or the addition of a C:N assessment in mandatory soil tests, should be implemented.

Biosolids have variable nutrient concentrations and mineralization rates depending on the associated wastewater treatment process (Cogger et al., 2004). If the nutrient concentrations are known, biosolids could make an excellent general fertilizer providing N, P, K, S, as well as the full range of micronutrients. However, based on this study, the use of anaerobically digested, thermally stabilized biosolids to raise the OM concentration (by weight) of furnished topsoil by 20% or more is not advised. Biosolids raised the initial SS concentration of soil above the maximum MDOT SHA limit. While the grasses used in this study have salt tolerances that exceed the maximum limit for furnished topsoil established by MDOT SHA, other plant selections could be susceptible to the higher salt concentrations in biosolid amendments. More importantly, PAN and/or mineralization was in excess of plant uptake, which led to higher N leachate losses from BAT as compared to the other treatments. Furthermore, percent coverage was comparable to LAT but significantly higher growth rates could lead to increased maintenance requirements. Finally, high soil PAN concentrations reduced root growth, which could diminish shoot growth over time, especially under heat and drought stress (Brown et al., 2010).

Chapter 4: The Effects of Age and Wood Fines on Biosolid Amendments and Impacts on Fertility and Nutrient Losses

4.1 Introduction

Biosolids, sometimes referred to as sewage sludge, are the organic solids removed from wastewater. After meeting requirements to reduce pathogens, vector attraction, and heavy metals, they may be applied to land according to federal, state, and local regulations. Rising interest in recovering nutrient resources from organic wastes has led many to proclaim the role biosolids play in improving soil. This is because biosolids are rich in nitrogen (N) and phosphorus (P) as well as a good source for most micronutrients (Boen and Haraldsen, 2011). In addition, biosolids are a source of soil organic matter, which is known to improve the physical properties of soil such as water retention, bulk density, porosity, and penetration (Tsadilas et al., 2005; Zhu, 2019). For all these reasons, at least 40% of all biosolids produced in the United States were applied to agricultural land in 2018 with another 11% distributed for use in agriculture or landscaping (Beecher et al., 2022).

The US Environmental Protection Agency (EPA) categorizes biosolids based on their quality and defines use restrictions in US EPA Part 503 - Biosolids Rule (Standards for the Use or Disposal of Sewage Sludge 40 C.F.F. Part 503). Until development of their most stringent standards for Class A Exception Quality (EQ) biosolids, land application was mostly constricted to agricultural land, forests, or reclamation sites. However, development of Class A EQ standards made utilization of biosolids in landscape settings more feasible by waiving Part 503 general requirements. After decades of use in agriculture, extensive research has been conducted to evaluate the agronomic value of biosolids as well as associated pollution risks (Cox et al., 2004; Rigby et al., 2016). High rates of nitrate leaching are well documented (Daniels et al., 2003). Therefore, application rates have traditionally focused on N agronomic rates to reduce nitrate pollution, as required by Part 503 rules. Because the N:P ratio in biosolids is low and because the Part 503 rule does not specify P rates, application of biosolids at agronomic N rates can result in the build-up of soil P (Schroder et al., 2008; Alvarez-Campos et al., 2018; Badzmierowski et al., 2020).

Extensive research has been conducted on the risk of P transport from biosolids applications. The general consensus is that even though P inputs to soil are high, P remains stable in soils with low phosphorus saturation ratio (PSR) values. Phosphorus Saturation Ratio refers to the capacity of soil to store P and methods for calculating it are generally determined by the amount of phosphorus, iron, and aluminum in solution (Nair, 2014). For example, White et al. (2010) provided direct evidence that iron (Fe) and aluminum (Al) additions mitigated P transport and furthermore showed that wastewater treatment plant processes are important factors affecting the availability of Fe and Al in biosolids. They showed that when iron chloride ($FeCl_3$) was used to reduce P solubility in wastewater, biosolids did not increase the soil PSR and the potential for dissolved reactive-P transport was reduced. Likewise, Maguire et al. (2000) investigated the influence of biosolids at eleven Mid-Atlantic sites. Those that received biosolids had significantly greater topsoil P concentrations as well as higher Fe and Al concentrations; therefore, the degree of phosphorus saturation was not always increased. These findings led Maguire et al. (2000) to conclude that adding biosolids according to N-based guidelines led to P accumulation; however, P release was mitigated by the associated increases to soil Fe and Al. Although these studies provide assurance that P loads from biosolids remain stable in soil, conclusions are based on the assumption that application rates are limited by N agronomic rates.

Part 503 rules do not apply to landscaping and gardening and are therefore not limited to N agronomic rates.

Compared to commercial fertilizers, biosolids have lower nutrient values that range from 1.5-7.5% for N, 1.5 – 3 % for P, and 0.1 to 0.6% for K (Lu et al., 2012; Rigby et al., 2016). The majority of N (50-90%) in biosolids is organically bound and mineralizable N is influenced by wastewater treatment practices, biological stabilization, and storage (Rigby et al., 2016). An extensive review by Rigby et al. (2016) examined the N mineralization rate of biosolids applied to agricultural land under a wide range of climatic and experimental conditions. Mean values of mineralizable-N, as a proportion of organic-N were as high as 47% for aerobically digested biosolids and as low as 7% for composted biosolids.

Since Class A EQ designation widened the pool of potential biosolids users, including people not trained in deciphering soil N and P availability and plant needs, application rates that exceed plant needs may be more commonplace. This leads researchers to question the collective impacts of biosolids on soil fertility and water quality with associated activities such as urban soil rehabilitation and turfgrass establishment. Additionally, research has focused on the nutrient value of "market-ready" products and doesn't portray what happens to these biologically active soil amendments after they are market-ready. Therefore, questions arise about the quality of stockpiled and/or stored biosolids since storage conditions and microbes may alter their nutrient value.

Only two studies have been found that compared the N availability and mineralization of biosolids based on age. Rouch et al. (2011), demonstrated that the quality of biosolids as a soil improver and N fertilizer was significantly diminished by age. Treatments included air dried anaerobically digested biosolids that ranged in age from 0-36 months old. Fresh samples were taken upon output from the digester and were therefore, not dried or market ready. Bernal et al. (1998) focused on composted biosolids and measured N mineralization at different points in the composting process. Results demonstrated that the composition ratio of plant available N to TN changed throughout the process. The greatest N fertilizer value came from the mature biosolids compost which had a high concentration of NO_3^-. One study was identified that compared market ready fertilizer values of different biosolids based on the method used to dewater them; however, post market values were not discussed. In that study, the TN concentration for air-dried biosolids was 2.8% (dry basis) compared to 5% (dry basis) for mechanically dewatered biosolids (Rigby et al., 2016). This last study is mentioned because air-drying takes time, which may provide insight into how post-consumer biosolids products are changed during this time.

The biosolids industry and researchers have made considerable efforts to develop biosolids products which meet the needs for general use. To be marketable, products must be easy to handle, easy to incorporate, and most important – they must provide enhanced fertility. Mixtures that combine biosolids with various wood waste products reliably meet those needs (Alvarez-Campos et al., 2018; Badzmierowski et al., 2019; Zhu, 2019). Such biosolids/wood fines (BWF) co-amendments have the added benefit of reducing nitrate losses on a volume-to-volume basis; however, mixed amendments have lower N content values (Daniels et al., 2003; Paramashivam, 2015). This leads one to wonder if aged BWFs retain their fertility and if not, what the degree of loss is compared to pure, aged, commercially available biosolids.

Online marketing materials for a local commercial biosolids producer recommend incorporating up to 35% (of a woody blend) for turfgrass establishment and 25% (fresh biosolids) for commercial topsoil mixes or onsite mixing at construction sites (https://bloomsoil.com/about-bloom-soil-amendment/). Given that the range for biosolids N is between 1.5% and 7%, these application rates likely exceed turfgrass N needs. The estimated area of land cultivated for turfgrasses in the United States is 163,800 km^2 - 3× higher than the area for any irrigated crop (Milesi et al., 2005). Therefore, the collective effects from nutrient leaching associated with biosolids and turfgrass establishment could have a significant impact on the environment at incorporation rates such as those described above. Benchmarks should be established for comparing biosolids products and rates to better understand the impact of biosolids usage in non-agricultural settings. Such benchmarks will allow nutrient managers to improve sustainable biosolids practices.

4.1.1 Research Objectives

1. To establish a method for examining recommendation rates for biosolids applied for turfgrass establishment and/or rehabilitation of disturbed urban soil. Assessments were made using UMD's recommended rate for organic amendments (2.54 cm, incorporated) to provide a benchmark for other variables and for future studies.
2. To determine the effects of aging and wood fines on the fertilizer value of the selected biosolid product, leaching potential, as well as actual N and P leachate mass losses when biosolids were applied to soil.
3. To compare leaching losses from biosolid amendments incorporated into soil at 1:4 (v/v) ratios with starter fertilizer (20-16-12) incorporated into the same volume of soil at rate of 44 kg-N·ha^1 during the establishment of a cool season seed mixture.

4.2 Materials and Methods

4.2.1 Amendment Analysis

The new and aged biosolids product selected for this research, Fresh Bloom® (Blue Plains WWTP, Washington, DC), met EPA Class A EQ requirements. The product was chosen because it is easily attainable throughout Maryland. It is produced through anaerobic digestion and is dewatered by mechanical pressing. During the treatment process, metal salts such as ferric chloride, ferrous sulfate and liquid alum, may be used to precipitate phosphorus and enhance settlement. Additionally, lime is applied to effluent to maintain an adequate pH level ("Blue Plains NPDES Factsheet," 2017). Fresh Bloom® was sourced directly from the production line for use in these experiments. Two-year-old Fresh Bloom® and hard wood fines were acquired from Grant County Mulch (Laurel, Maryland), where the products were stored in non-covered stockpiles. Wood fines have a consistency similar to sawdust and are ground from woody debris sourced from land clearing activities, sawmills, and landscapers. New biosolid (NB) and old biosolid (OB) were mixed with wood fines (WF) at the University of Maryland (UMD) at a 1:1 (v/v) ratio to form the OBWF and NBWF co-amendment treatments. Samples of each treatment were sent to Matrix Sciences (Chicago, IL) for a complete compost analysis before use in these studies. Matrix Sciences (formerly Agrolab, Harrington, DE) is a US Composting Council Seal of Testing Assurance (STA) Compost-Certified Laboratory that follows TMECC guidelines. Results are listed on an 'as is' and 'dry' basis for discussion. However, they were applied 'as is' in these experiments.

4.2.2 Column Study

The amendments described above (NB, OB, NBWF, and OBWF) were included in a short-term column nutrient leaching study, to measure N and P losses when amendments were leached with 350 mL aliquots of deionized water each week for five weeks. A number of replicate columns (four per treatment) were constructed using 130 mm Buchner Funnels (Fisher Scientific; Pittsburg, PA) and PVC pipe with an inside diameter of 118 mm (Figure 4.1).

Figure 4.1. A column study was conducted to determine nitrogen and phosphorus loses from four soil amendments: new biosolids, old biosolids, new biosolids with wood fines, and old biosolids with wood fines. Columns were loaded with soil to a depth of 63.5 mm and received a total of 1.75 L of deionized water, the equivalent of 158.8 mm of simulated rainfall, over 5 weekly leaching events.

Before loading samples, a permeable green roof geotextile filter (Standard Duty Separation Fabric, Conservation Technology; Baltimore, MD) was placed at the bottom of each column to hold biosolids within the columns while allowing water to pass through. The first column from each treatment was loaded by filling the column to a depth of 6.35 cm. Columns were then dropped three times from a 30 cm height, to compact the column sample. Columns were refilled to a depth of 6.35 cm and the process repeated a second time. Columns were filled a third time to 6.35 cm and then weighed. The remaining 3 columns for each treatment were filled with an equivalent weight of material and tamped down to compacted the contents to a depth of 6.35 cm. This process allowed for equal bulk density within each column by treatment, which was 0.68 g·cm^{-3}, 0.59 g·cm^{-3}, 0.57 g·cm^{-3}, and 0.57 g·cm^{-3} for NB, OB, NBWF and OBWF, respectively.

To induce leaching, 350 mL of deionized (DI) water, the equivalent of a 31.75 mm rainfall, was applied weekly for five weeks. Water was poured into a plastic drain coupling holding a metal end cap at the top of each column. Holes (1 mm) were driven into the end caps to allow water to drain evenly onto the amendment contained within each column. Columns drained into clean 500 mL glass flasks. The volume of leachate collected in each flask was recorded at the cessation of leaching to normalize nutrient mass loss calculations (concentration × leachate volume). Then, leachate samples (3 per column) were transferred into 75 mL plastic bottles. They were put into storage immediately upon collection at -40°C until analysis.

Each sample was analyzed in the UMD Environmental Engineering Lab (EEL) for the following: total phosphorus (TP), orthophosphate (Ortho P), and total dissolved phosphorus (TDP). To prepare samples for analysis of Ortho P and TDP, approximately 60 mL of each sample was filtered through a 0.45 µm Tisch Scientific (Cleves, OH) glass fiber syringe filter to remove particulates. For unfiltered TP samples and filtered TDP samples, 25 mL aliquots were digested in a HotBlock™ (Environmental Express, Charleston, SC) following EPA method 365.1 for digestion. Prepared samples were analyzed on a SEAL AQ300 Nutrient Analyzer (Porvair PLC, Kings Lynn, UK) for Ortho P. The method detection limit (MDL) for phosphate was 0.01 mg·L^{-1}. Particulate P (PP) was estimated using the following equation:

$$PP = TP - TDP.$$

Nitrate/nitrite (NOx) and ammonium (NH_4^+) were also assessed in the EEL on the SEAL AQ300 using filtered samples. For NOx, samples were analyzed using EPA Method 353.2 (MDL = 0.01), and EPA Method 350.1 was used for NH_4^+ (MDL = 0.05). Lastly, frozen samples were sent to the University of Delaware Soil Testing Lab (Newark, DE) to be analyzed for total nitrogen (TN) using the high temperature/catalytic combustion oxidation method (720° C, MDL = 0.1 mg·L^{-1}). Organic N was estimated using the following equation:

$$\text{Organic N} = \text{TN} - \text{NOx} - NH_4^+$$

4.2.3 Greenhouse Biosolid Leachate Study

A greenhouse (GH) microcosm study was conducted at the University of Maryland's Greenhouse Complex in College Park, MD from Sept 2022 to Nov 2022 to measure N and P mass leachate losses from a control soil (C), soil amended with one of three biosolid amendments (NB, NBWF or OBWF), and fertilized soil (F). The fertilized soil treatment received a 20-16-12 (N-P_2O_5-K_2O) starter fertilizer for turfgrass that contained 11.6% water insoluble N as ureaform (Growmark FS, LLC., East Berlin, PA). The fertilizer was applied at a surface application rate of 44 kg-N·ha^{-1} (39 lbs-N·acre^{-1}). Biosolid amendments were applied "as is" to a depth of 2.54 cm and were incorporated as described below. These fertilizer and amendment rates complied with Maryland's nutrient management requirements for turfgrass seeding and sod installation (Carroll and Turner, 2016). Soil organic matter, pH, nitrate, ammonium, and Mehlich-3 P, Ca, Fe, and Al were tested by Matrix Sciences at the beginning and end of the experiment using the methods described in Table 3.2. Additionally, the phosphorus saturation ratio (PSR), which refers to the capacity of soil to store P, was calculated based on the amount of phosphorus, iron, and aluminum in solution (Nair, 2014).

Microcosms were constructed from 51 × 74 cm plastic tubs (4 replicate tubs/treatment) that permitted the collection of subsurface leachates (Figure 4.2). Each microcosm was shimmed creating a 25:1 slope to direct leachate towards drainage holes that were drilled into the bottom of the microcosms. A permeable green roof geotextile filter (same as above mentioned) held soil within the tubs while allowing water to pass through the drainage holes. Plastic gutters directed leachate to designated clean 22.7 L plastic collection buckets.

Figure 4.2. Simulated rain events equivalent to 25.4 mm of rainwater were applied biweekly to greenhouse microcosms to measure nitrogen and phosphorus leachate totals from fertilized soil or soil amended with one of four biosolids treatments: new biosolids, new biosolids and wood fines, or old biosolids and wood fines. Microcosms were designed to collect leachate in plastic gutters that diverted it to 22.7 L plastic collection buckets.

The topsoil used in the GH study came from Pleasants Construction, Inc (Clarksburg, MD), sourced from a forested area that was cleared for development. Soil was stored in an exposed stockpile for at least one year before it was received. Tubs receiving the C and F treatments were filled to a depth of 10.16 cm with soil. Tubs receiving NB, NBWF and OBWF were filled to a depth of 12.7 cm, which included 10.16 cm of soil and 2.54 cm of amendment. The volume of soil and amendment needed to fill each tub to these specifications was poured into a wheel barrow on a tub-by-tub basis. After materials were thoroughly and evenly mixed by hand, the contents of the wheel barrow were transferred to a prepared tub. Microcosms were randomized by treatment on three benches in the UMD Greenhouse Complex.

Removable rain simulators (Pictured in Chapter 3, Figure 3.1), constructed from tubs identical to the microcosm tubs, were suspended 25.4 cm above the microcosms during SREs. Biweekly rain events equivalent to 25.4 mm rainstorms (8,720 mL) were applied to each tub at an approximate rate of 101.6 mm/hr. To distribute rainfall equally over the surface of the microcosms, 18 – 21 holes (1 mm) were drilled into the simulators. Drainage time for each SRE was measured to ensure consistency. After filling tubs and before seeding them, microcosms received one SRE. Four additional SRE's were applied after seeding. Tap water was used as a proxy for rainwater for the study. Limited supplemental water was applied (as needed) to aid germination and growth between SREs. However, only enough water to wet the soil surface was applied and not enough to produce leachate. The volume of the leachate collected in each bucket was measured after every rain event. Samples, including tap water aliquots, were immediately frozen at -40°C until they were analyzed in the EEL for TP, Ortho P, and NOx, as described above. A frozen set of samples was sent to the UD Soil Testing Lab for additional analysis of TN and NH_4^+, which were processed using the methods described above.

On Oct 5, 2022 microcosms were seeded with a cool season turfgrass seed mix (Newsome Seed; Fulton, MD) consisting of two tall fescue cultivars and one Kentucky Bluegrass: *Festuca arundinacea* 'Wichita' (49.69%), *Festuca arundinacea* 'Gold Medallion' (44.76%) and *Poa pratensis* 'Wild Horse' (4.98%). Seeds were applied at a rate of 224 $kg \cdot ha^{-1}$ (8.32 g/tub). Treatment effects on turfgrass growth are presented in Chapter 5.

4.2.4 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 and leachate losses ($\alpha = 0.05$). When ANOVA revealed that there was a statistically significant difference between at least two groups, a post-hoc test was performed using either the Bonferroni Correction or the Games-Howell test for instances where variance was unequal. Repeated measures ANOVA was performed on leachate samples to assess the main effects the successive SREs on nutrient losses. When sphericity was not met, a Greenhouse-Geisser correction was used to determine the significance of effects. Where indicated, a two-way ANOVA was used to assess whether aging and wood fines interacted to effect results. In some places the strength of a linear relationship is indicated with partial eta squared (ηp2). This is the statistic that is given in SPSS and is similar to R^2, which ranges from 0 to 1. The closer to 1, the more positive the relationship. Lastly, pairwise t-tests were performed on select before/after soil measurements to determine if nutrient concentrations were statistically different. When statistical differences are mentioned, treatment means, standard errors (SE), p-values, and ηp2 (where applicable) are listed within the text or the specified table/figure.

4.3 Results and Discussion

4.3.1 Amendment Analysis

Wood fines decreased the bulk density of amendments nearly 31% (Table 4.1), whereas aging of biosolid amendments had no effect. In an experiment that examined compost effects on soil physical properties, other researchers showed that soil bulk density decreased with increasing total carbon inputs (Gonzalez and Cooperband, 2002). The result was greater aggregate stability and formation, which is associated with improved soil structure. Another study compared the physical properties of soil amended with pure biosolids to soil amended with biosolids, sawdust, and sand. Mixtures improved physical properties more than pure biosolids.

Table 4.1: Nutrient analysis for wood fines (WF) and four biosolids amendments: new biosolids (NB), two-year-old biosolids (OB), NB with wood fines (NBWF) and OB with wood fines (OBWF). Biosolids and WF co-amendments were mixed at a 1:1 ratio. Results are reported on an 'as is' (A) and dry (D) basis.

Measurement	Basis	WF	NB	OB	NBWF	OBWF
Bulk Density ($kg \cdot m^{-3}$)	A	481	673	673	449	481
% Moisture Content	-	41.33	67.44	58.49	56.97	52.92
% Dry Matter	-	58.67	32.56	41.51	43.93	47.08
C:N Ratio	-	46	7.6	11.1	13.5	14.7
pH	A	7.7	8.8	5.6	7.5	7.8
EC ($dS \cdot M^{-1}$)	A	0.20	1.41	1.5	1.97	0.16
%Organic Matter	A	22.33	18.03	20.03	24.37	23.32
	D	38.06	55.39	48.25	55.47	49.54
% Organic C	A	12.95	10.46	11.61	14.13	13.53
	D	22.08	32.13	27.98	32.17	28.73
% Organic N	A	0.25	1.3	0.94	0.93	0.08
	D	0.43	4.00	2.26	2.21	1.69
% Ammonium	A	0.025	0.075	0.039	0.116	0.116
	D	0.042	0.230	0.094	0.263	0.246
% Nitrate	A	0.004	0.001	0.066	0.002	0.008
	D	0.006	0.004	0.159	0.005	0.017
% Total N	A	0.28	1.38	1.04	1.05	0.92
	D	0.48	4.23	2.51	2.39	1.95
% P_2O_5	A	0.08	2.05	2.10	0.90	1.12
	D	0.14	6.29	5.06	2.04	2.38
% K_2O	A	0.19	0.03	0.13	0.06	0.11
	D	0.32	0.08	0.31	0.14	0.23
% S	A	0.04	0.30	0.29	0.20	0.16
	D	0.07	0.92	0.70	0.45	0.34
% Ca	A	0.86	0.74	1.18	0.54	0.84
	D	1.47	2.26	2.85	1.23	1.78
%Mg	A	0.15	0.10	0.17	0.10	0.13
	D	0.25	0.31	0.41	0.23	0.28
% Na	A	0.01	0.01	0.01	0.01	0.01
	D	0.02	0.03	0.03	0.02	0.03
Zn (ppm)	A	52.7	207.8	193.1	123.9	101.8
	D	89.8	638.3	465.1	282.1	216.2
Fe (ppm)	A	7128	24220	23976	12567	13134
	D	12150	74386	57758	28607	27896
Mn (ppm)	A	171.8	131.9	252.2	102.6	143.5
	D	292.8	405.0	607.5	233.5	304.9
Cu (ppm)	A	7.7	116.8	105.4	59.7	44.5
	D	13.5	358.8	253.9	135.9	94.6
Al (ppm)	A	3234.1	1099.4	1986.7	1216.4	1397.0
	D	5512.4	3376.4	4786.1	2769.0	2967.5
B (ppm)	A	7.9	20.6	23.0	8.1	9.3
	D	13.5	63.2	55.4	18.4	19.7

Aging and wood fines increased the C:N ratio of biosolids (Table 4.1), which ranged from 7.6 in NB to 14.7 in OBWF. The potential for N to mineralize is negatively associated with the C:N ratio (Shin et al., 2016). However, immobilization is not likely to occur at the observed ratios. Cogger (2005), reported in a review of composts that C:N ratios less than 20:1 provided significant amounts of N and other nutrients, which in turn improved turfgrass and landscape plant establishment. Therefore, the NB, OB, NBWF and OBWF products examined in this study are likely to provide plant available nutrients immediately upon incorporation, although at different amounts as the results show (Table 4.1). Apart from N, aging did not decrease the concentration of macro nutrients (as is). However, it did decrease the concentration of some micronutrients including Fe, Zn, and Cu. On the other hand, the addition of WF to biosolids decreased nearly all nutrient concentrations.

Aging decreased the pH of biosolids, but biosolid addition did not greatly affect the pH of WF when mixed together (Table 4.1). The low pH observed in OB (5.6) was most likely caused by nitrification. During this process, H+ is released as NH4+ is converted to NO3-. Agronomist have long described soil acidification following the application of nitrogenous fertilizers, especially those with high concentrations of ammonium (Pierre, 1928). Here, a lower concentration of organic-N in OB (0.94%) compared to NB (1.3%) suggests that mineralization had taken place during storage of the commercial biosolids product, resulting in a low pH value for OB. Diminished organic-N also means that OB has less mineralizable N available to replace N that is taken up or leached, which decreases its long-term nutrient value.

A broader look at TN demonstrates that aging decreased the concentration of N in OB by 25%. Since OB was not stored in a closed system, the diminished concentration is attributed to nitrate leaching, volatilization, and/or denitrification. A loss of this magnitude shows that aged, mechanically-dewatered biosolids, such as Fresh Bloom®, experience similar degrees of TN loss as air-dried biosolids. Here, the TN concentration was 4.23% (dry basis) for NB and 2.51% (dry basis) for OB. Rigby et al. (2016) reported means of 5% (dry basis) for mechanically dewatered biosolids and 2.8% (dry basis) for air dried biosolids. These results show that long-term storage decreases TN and mineralizable N for at least one market-ready biosolid product. The implication for these findings is that secondary dealers and users should be made aware that fertilizer values for biosolids could diminish over time.

Wood fines and aging had similar effects on the concentrations of TN and organic N as seen in the results for OB and NBWF (Table 4.1). However, concentrations were further reduced when WF and aging were combined. As such, the TN concentration for OBWF was 33% less than NB and organic N was 38% less. Wood fines did not change the concentration of nitrate in NB in a meaningful way because WF, NB and NBWF had similar concentrations. However, WF reduced the concentration of nitrate in aged biosolids from 0.066% to 0.008%. Enhanced carbon availability for microbial nitrification/denitrification is likely responsible for reduced nitrate. Both NBWF and OBWF had higher concentrations of ammonium than their counterparts. This may be evidence that adding high carbon WF spurred nitrification/denitrification. However, this suggestion can't be substantiated at this time as we did not measure this, and it will require further investigation. Regardless, these findings show that WF decrease overall TN, which may be goal for some biosolids users focused on improving the physical characteristics of soil and/or reducing N losses.

Contrary to the results for TN, aging did not have a large impact on the concentration of TP (expressed as P_2O_5, Table 4.1). Concentrations for NB and OB were 2.05% and 2.1% (as is), respectively. Unlike N, the P cycle does not include gaseous losses. Therefore, P losses from stockpiled biosolids are typically attributed to stormwater runoff and leaching. Because stockpiled biosolids are known to form a crust that sheds precipitation and prevents significant percolation, transport through water is minimized ("Recommended Management Practices," 2000). On the other hand, WF reduced TP by 56% in NBWF and 46% in OBWF. Since the concentration of P in WF was less than NB and OB, dilution is the most obvious explanation. These findings imply that 1) aging of commercial ready biosolids does not decrease their "as is" P concentration, and 2) WF are an effective tool for reducing P loads to soil amended with biosolids.

Based on amendment nutrient concentrations (Table 4.1), bulk densities (Table 4.1) and an application rate of 2.54 cm spread over land, N and P loads (kg·ha-1) were calculated and are listed in Table 4.2. An example calculation is included in Appendix D. Additionally, nutrient loading rates are provided in $kg \cdot MT^{-1}$ on a "dry basis" and "as is" basis in Table 4.3. The treatments provided 128-179 $kg \cdot ha^{-1}$ of nitrate and ammonium, as well as 970-2222 kg of organic-$N \cdot ha^{-1}$ (Table 4.2), a portion of which would be expected to mineralize in the first year. A typical starter fertilizer rate is 48.8 kg-$N \cdot ha^{-1}$ when surface applied and 97.6 kg-$N \cdot ha^{-1}$ when incorporated (Carrow et al., 2001). Based on ammonium and nitrate concentrations alone, 2.54 cm of these biosolids products over land will exceed N recommendations for turfgrass establishment. First year nitrogen mineralization rates for biosolids are wide-ranging: 47% for aerobically digested, 40% for thermally dried, 34% for lime treated, 30% for mesophilic anaerobically digested, and 7% for composted biosolids (Rigby et al., 2016). Using the lowest mineralization rate for composted biosolids (7%) and the organic-N loading rates in Table 4.2, an additional 68-156 $kg \cdot ha^{-1}$ would be available in the first year. This means that when NB, OB, NBWF, and OBWF are applied to land at 2.54 cm for the purpose of establishing turfgrass, excess N will be applied which could result in N pollution.

Table 4.2: Total nitrogen (TN), soluble nitrogen (NH_4^+ & NO_3^-), organic-N, and phosphorus (expressed as P_2O_5) loads when biosolids are applied at a depth of 2.54 cm. Amendments include new biosolids (NB), two-year-old biosolids (OB), NB with wood fines (NBWF) and OB with wood fines (OBWF).

Amendment	TN $kg{\cdot}ha^{-1}$	NH_4^+ & NO_3^- $kg{\cdot}ha^{-1}$	Organic-N $kg{\cdot}ha^{-1}$	P_2O_5 $kg{\cdot}ha^{-1}$
NB	2361	128	2222	3495
OB	1777	179	1598	3589
NBWF	1196	131	1059	1020
OBWF	1123	153	970	1367

Table 4.3: Nutrient loading rates for four biosolids amendments: new biosolids (NB), two-year-old biosolids (OB), NB with wood fines (NBWF) and OB with wood fines (OBWF). Co-amendments were mixed at a 1:1 ratio. Results are reported on a dry and 'as is' basis since moisture content can affect loading rates.

	Dry Basis $kg{\cdot}MT^{-1}$				**As Is Basis** $kg{\cdot}MT^{-1}$			
	NB	**OB**	**NBWF**	**OBWF**	**NB**	**OB**	**NBWF**	**OBWF**
Organic-N	39.9	22.5	21.2	16.8	13.0	9.3	9.3	7.9
NH_4^+	2.3	0.9	2.6	2.4	0.7	0.4	1.1	1.1
NO_3^-	0.0	1.6	0.0	0.1	0.0	0.6	0.0	0.1
Total N	42.3	25.1	23.9	19.5	13.7	10.4	10.5	9.2
P (P_2O_5)	62.8	50.5	20.4	23.7	20.4	21.0	8.9	11.2
K (K_2O)	0.8	3.1	1.4	2.3	0.2	1.3	0.6	1.0
S	9.2	7.0	4.4	3.4	3.0	2.9	1.9	1.6
Ca	22.6	28.5	12.3	17.8	7.3	11.8	5.4	8.4
Mg	3.0	4.0	2.3	2.7	1.0	1.7	1.0	1.3
Na	0.3	0.3	0.2	0.3	0.1	0.1	0.1	0.1
Zn	0.6	0.4	0.3	0.2	0.2	0.2	0.1	0.1
Fe	74.4	57.7	28.6	27.9	24.2	23.9	12.5	13.1
Mn	0.4	0.6	0.2	0.3	0.1	0.2	0.1	0.1
Cu	0.3	0.2	0.1	0.1	0.1	0.0	0.0	0.0
Al	3.4	4.8	2.7	2.9	1.1	2.0	1.2	1.4
B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Phosphorus loading rates for NB, OB, NBWF and OBWF applied to a depth of 2.54 cm range from 1367-3589 kg-P_2O_5·ha^{-1} (445-1566 kg-P·ha^{-1}, Table 4.2). There is variability in the forms of P present in biosolids, which is influenced by wastewater treatment processes (Ahmad et al., 2019). Therefore, not all of the P present in biosolids is immediately labile. Phosphorus recommendation rates are more complicated than N since buffering capacity controls the supply of soluble P (Daly et al., 2015). Carrow et al. (2001) recommends 49 kg- P_2O_5·ha^{-1} on soils with sufficient soil P test results or where deficiencies are not expected. Two applications are recommended where soil P is unknown or limited: 98 kg·ha^{-1} to be mixed into the root zone (up to 10.16 cm) and an additional 49-98 kg·ha^{-1} to be surface applied just prior to or after seeding.

Based on the amendment analysis results and the highest rate for P deficient soil recommended by Carrow et al. (2001), 195.2 kg-P_2O_5·ha^{-1}, P will be over-applied (by between 7 and 18 times) when 2.54 cm of NB, OB, NBWF, and OBWF are applied over land. However, much of the P contained in these amendments will not be plant-available due to the presence of Fe. Phosphorus availability then becomes the key question. Numerous studies demonstrated TP, PSR, Mehlich-3 P (M3P), and water soluble P increases followed biosolids applications (Penn and Sims, 2002; Schroder et al., 2008; Hosseinpur and Pashamokhtari, 2013). Increases in availability were correlated with application rates that were typically below 200 kg-P·ha^{-1}. This implies that soils that have biosolids applied to a depth of 2.54 cm will likely receive significant increases in TP, M3P, and potentially PSR values. These changes could raise leaching concerns but not necessarily plant available P.

4.3.2 Column Study Results

4.3.2.1 Particulate Phosphorus and Total Phosphorus

A two-way repeated measures ANOVA was performed with a Greenhouse-Geisser correction to compare the effects of intermittent simulated rain on TP mass loss by treatment (Figure 4.3.A). Generally, TP leachate totals decreased over time with the exception of NBWF. However, the direction of the NBWF trend was not clear after evaluating within treatment pairwise comparisons. Mean NBWF TP leachate totals were lower for SRE3 and SRE4 than SRE1, SRE2 and SRE5 ($p < 0.001$). Therefore, it's uncertain whether the SRE5 NBWF increase was momentary or the beginning of an upward trend. Additional SREs would be needed to draw conclusions.

Most of the phosphorus transported in the column study was particulate bound. Particulate phosphorus comprised 69.6%, 71.2%, 69.2%, and 56.2%, of cumulative TP for NB, OB, NBWF, and OBWF, respectively. Because of this, weekly SRE TP and PP leachate mass losses reflected each other (Figure 3.A&B). This finding is supported by White et al. (2010), who showed that TP runoff totals from soil treated with biosolids were closely related to sediment transport. Since large portions of TP leachates were associated with particulate losses, diminishing totals were a result of fewer particulates leached after each SRE.

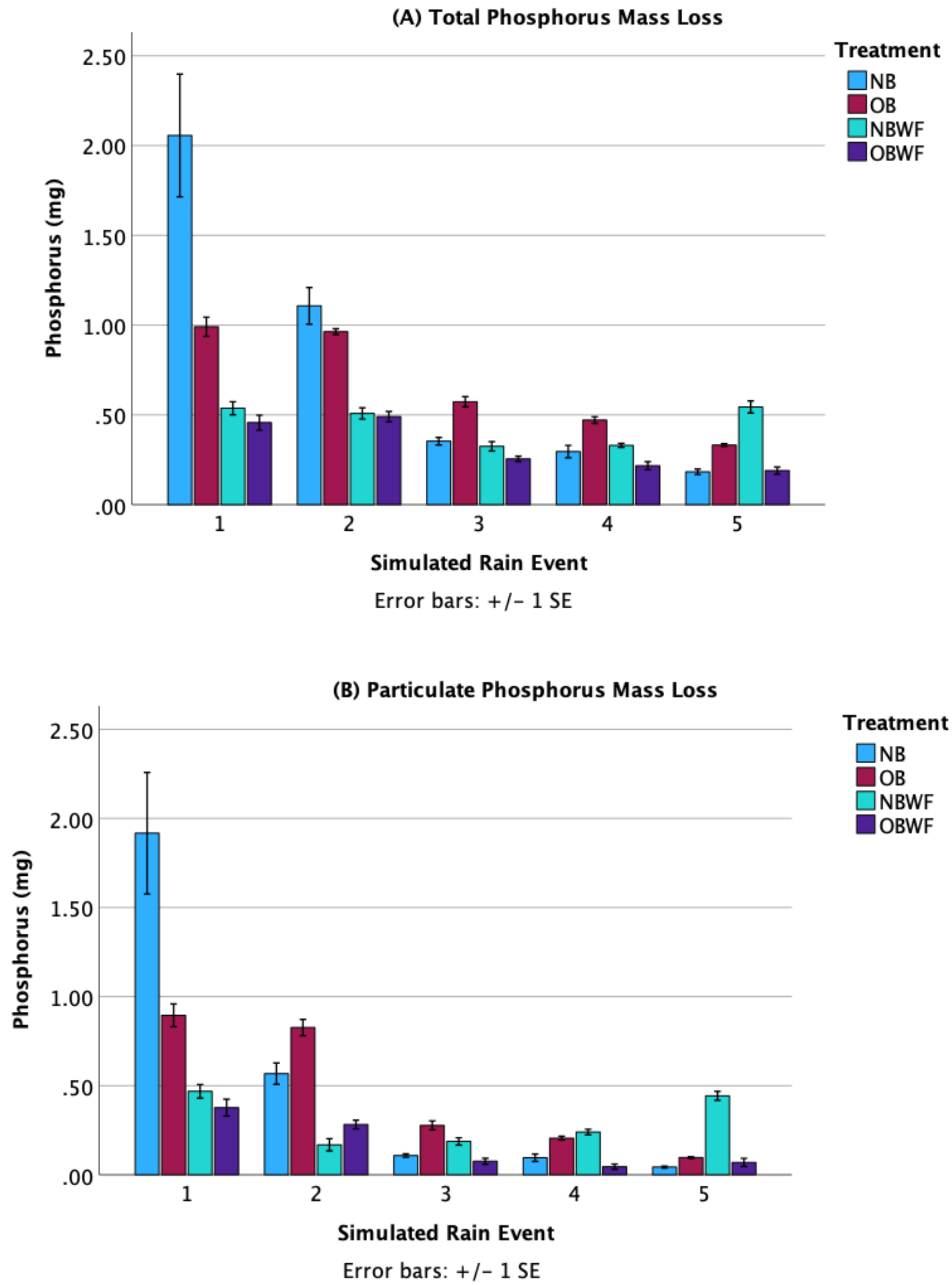


Figure 4.3. Column Study (A) total phosphorus and (B) particulate phosphorus mass losses by treatment and simulated rain event. Columns were loaded to a depth of 63.5 mm with either new biosolids (NB), old biosolids (OB), new biosolids with wood fines (NBWF) or old biosolids with wood fines (OBWF). Simulated rain events were equivalent to a 31.8 mm rainfall.

Cumulative NB and OB TP leachate totals were statistically similar and nearly 2 times higher than their BWF counterparts (Table 4.4). Due to the high variability in the NB TP mean for the first simulated rain event, a larger sample size would have likely provided a clearer picture of whether differences in NB and OB losses were truly insignificant. Similar P_2O_5 concentrations were noted in the amendment analysis for NB and OB, which supports similar cumulative TP mass loss findings. However, a two-way ANOVA that examined aging and WF, revealed that both factors had significant effects. Aging reduced phosphorus loss from fresh biosolids by 18%, and 27% in the BWF blends ($p = 0.015$, ηp = 0.427). However, wood fines had a greater effect. Cumulative TP mass loss totals were 44% and 50% less for NBWF and OBWF as compared counterparts ($p < 0.001$, ηp = 0.845). Reductions are attributed mainly to dilution of phosphorus concentrations in the co-amendments since WF had lower a concentration of P than NB and OB. However there is some evidence that wood chips remove small amounts of dissolved P in bioreactors through sorption with metals (Ca, Mg, Fe and Al) held within wood (Sanchez Bustamante-Bailon et al., 2022), which could have helped reduced overall TP losses. There was not a significant interaction between aging and WF on TP mass loss.

It should be noted that the total phosphorus leached from NB for the first two leaching events was especially high. The combined NB TP mass loss total for SRE1 and SRE2 was equal to the cumulative OB leachate (3.02 mg). Furthermore, the NB SRE1 total alone (2.06 mg) was similar to the cumulative NBWF total (2.2 mg) and greater than the cumulative OBWF total (1.6. mg). Together, these results indicate that WF reduce TP transport from fresh biosolids; however more research is needed to determine what effect aging has on overall losses.

Table 4.4: Column study cumulative leachate totals for total nitrogen (TN), ammonium ($NH4^+$), nitrate/nitrite (NOx), organic nitrogen (Organic-N), orthophosphate (Ortho P), total dissolved phosphorus (TDP), and total phosphorus (TP). Values in rows which have different letters are significantly different ($\alpha = 0.05$), as determined by ANOVA.

Treatment		NB	OB	NBWF	OBWF	p-value*
TP (mg)	Mean	3.9^b	3.2^b	2.2^a	1.6^a	<.001
	SE	0.4	0.1	0.1	0.1	
Ortho P (mg)	Mean	0.416^b	0.681^c	0.220^a	0.543^{bc}	<.001
	SE	0.04	0.02	0.03	0.04	
TDP (mg)	Mean	1.28^c	1.02^b	0.74^a	0.75^a	<.001
	SE	0.67	0.04	0.02	0.02	
NOx (mg)	Mean	31.2^a	136.3^c	55.3^b	57.4^b	<.001
	SE	2.2	7.2	2.5	1.8	
$NH4^+$ (mg)	Mean	378.4^d	178.3^c	131.7^b	54.9^a	<.001*
	SE	16.7	8.3	7.5	3.0	
Organic-N (mg)	Mean	279.1^c	101.7^b	84.4^b	28.3^a	<.001
	SE	5.2	8.1	7.5	2.6	
TN (mg)	Mean	699.0^d	416.3^c	271.4^b	143.1^a	<.001*
	SE	14.4	8.4	2.5	4.8	

* 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.

4.3.2.2 Total Dissolved Phosphorus

Although all phosphorus losses are important to measure, dissolved forms draw particular attention since they are available for metabolic use by plants and algae; and, dissolved P is a driver for eutrophication events in fresh water systems. Cumulative TDP leachate totals were different and occurred in the following pattern: NB > OB > OBWF = NBWF (Table 4.4).

Total dissolved phosphorus is comprised of (dissolved reactive) Ortho P and dissolved organic compounds. Orthophosphates were 32.5%, 66.3%, 29.7% and 72.4% of TDP for NB, OB, NBWF and OBWF, respectively (Table 4.4). Higher proportions of Ortho P in the aged products are explained by mineralization, which can be accelerated by storage practices. McGrath et al. (2005) showed that the solubility of P in chicken litter, an organic product, was affected by moisture. Dry storage caused little change in P speciation. However, wet storage increased concentrations of inorganic P, which in turn increased concentrations of reactive P in amended soils. The aged biosolids product used in this experiment was stored in a stockpile exposed to the elements for two years prior to the initiation of this study. Such storage conditions could have contributed to the higher Ortho P mass losses observed in OB and OBWF samples (Table 4.4) as well as the susceptibility for organic-P to mineralize throughout the course of the column study. Results showed that the Ortho P rate of loss increased after every SRE for OB (Figure 4.4). Additional studies would be useful for determining if dry storage affects P mineralization after biosolids are purchased.

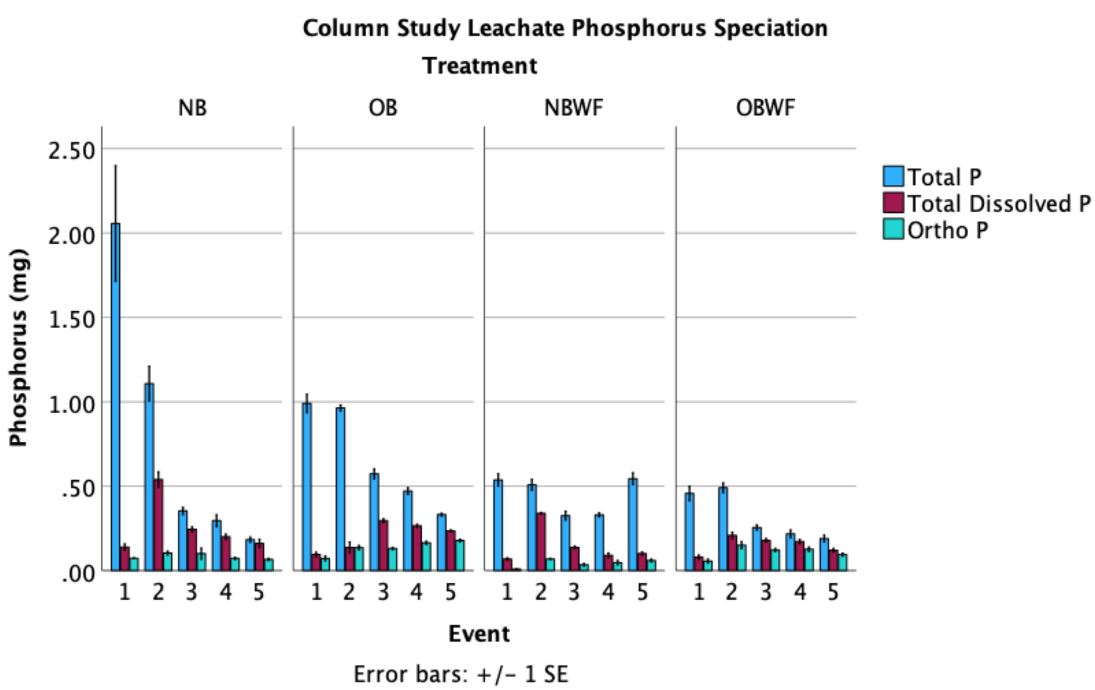


Figure 4.4. Phosphorus speciation for column study leachate by treatment and simulated rain event. Treatments included new biosolids (NB), old biosolids (OB), new biosolids with wood fines (NBWF) or old biosolids with wood fines (OBWF). Simulated rain events were equivalent to 31.8 mm rainfall, 350 mL of deionized water.

4.3.2.3 Nitrate/Nitrite

Combined nitrate and nitrite losses peaked during SRE2 for all treatments expect NBWF, which was relatively constant throughout the study (Figure 4.5). Delayed peaks for NB, OB and OBWF can be explained by the transformation of stored ammonium to nitrate following the first wet/dry cycle.

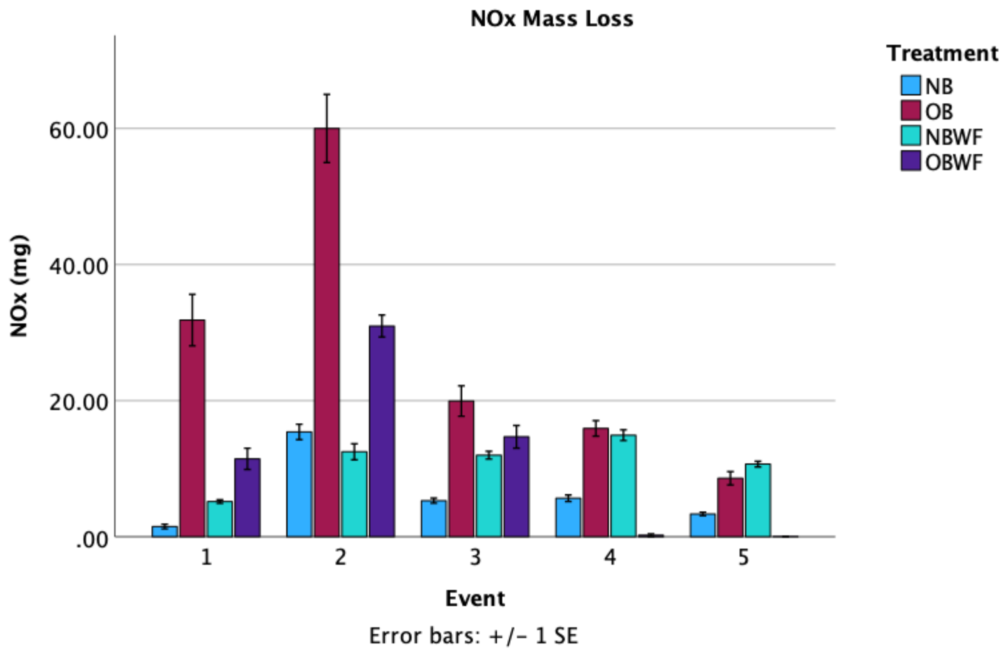


Figure 4.5. Column study combined nitrate and nitrite (NOx) leachate mass losses for simulated rain events by treatment. Columns were loaded to a depth of 63.5 mm with either new biosolids (NB), old biosolids (OB), new biosolids with wood fines (NBWF) or old biosolids with wood fines (OBWF). Simulated rain events were equivalent to 31.8 mm rainfall, 350 mL of deionized water.

Overall, the results show that aging increased NOx leaching (Table 4.4). Cumulative NOx leachate totals were greatest for OB, followed by the co-amendments, which were similar, and least for NB (136.3 mg, 55.3 mg, 57.4 mg, and 31.2 mg, respectively). High OB SRE1 and SRE2 NOx totals are explained by the amendment analysis, which showed that OB had the highest concentration of stored nitrate and second highest concentration of ammonium (Table

4.1). Initial low NB and NBWF NOx losses are likewise explained by the concentrations of NOx in the amendments at the beginning of the experiment.

The effect of WF on NOx leaching was more complicated. Wood fines decreased NOx leaching from OB but not NB. When comparing OB to OBWF, reduced leachate totals are explained by the lower concentration of NOx stored in OBWF. By SRE4, all preexisting and easily labile NOx was lost from the OBWF treatment such that NOx replacements were hardly detected (Figure 7). The pattern for OB NOx losses was similar. However, NOx leaching was still active, but declining, by the end of the experiment, indicating that the pool of organic N available for mineralization was still being transformed to measurable concentrations of NOx – albeit at a lower rate - with consecutive SREs. On the other hand, the results show that NOx losses for NB and NBWF entered a steady state by SRE3, which illustrates that pools of organic N were replacing NOx losses between SRE3 and SRE5 at consistent rates. Replacement occurred at a higher rate for NBWF than NB, which can be explained by the pH of the treatments. The optimum pH for nitrification ranges between 8 and 9 (Shammas, 1986). New biosolids had a pH of 8.8, whereas NBWF had a pH of 7.5. These results demonstrate that aged biosolids leach more NOx; however, the portion of TN comprised of NOx was small in comparison to other N forms.

4.3.2.4 Ammonium

Wood fines reduced cumulative ammonium mass losses by nearly 70% and aging reduced losses by at least 50% (Table 4.4). Ammonium losses were greater than NOx losses for each treatment, except OBWF, and comprised 54%, 43%, 48%, and 38% of cumulative N losses for NB, OB, NBWF, and OBWF, respectively. Cumulative totals were 378.4 mg, 178.3 mg, 131.7 mg, and 54.9 mg for NB, OB, NBWF, and OBWF, respectively. However, differences were greater in both fresh biosolids treatments as compared to their counterparts containing wood fines. Losses decreased linearly for each treatment between the first and last SRE (Figure 4.6).

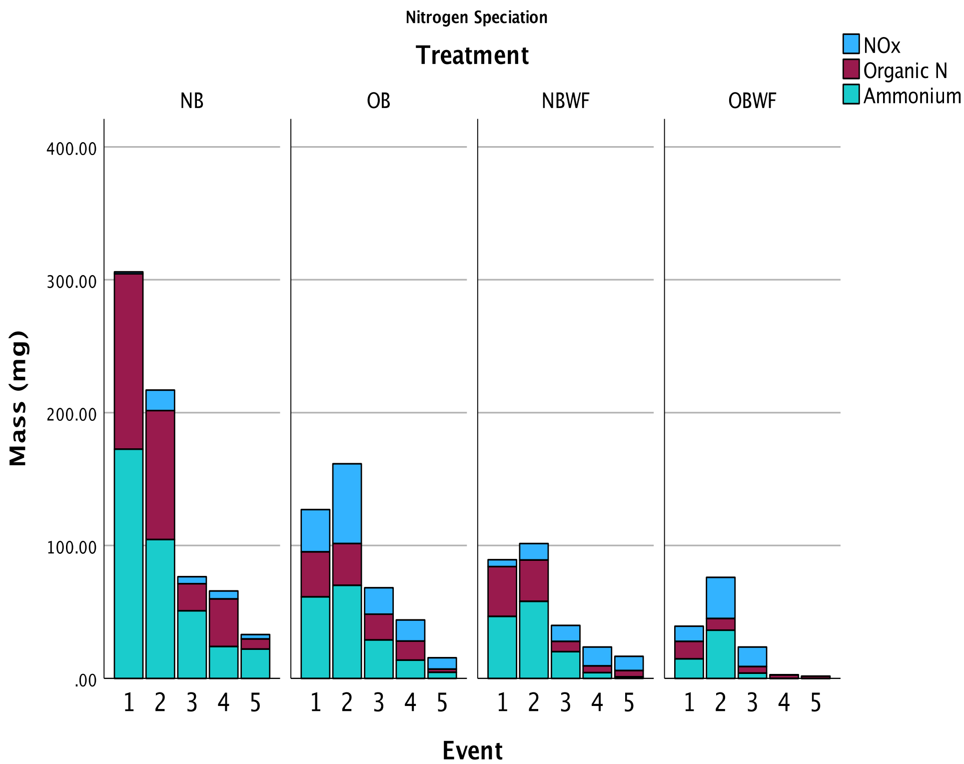


Figure 4.6. Nitrogen speciation for column study leachate by treatment and simulated rain event. The total amount of nitrogen leached is equivalent to the sum of nitrate/nitrite (NOx), organic N and ammonium. Columns were loaded to a depth of 63.5 mm with either new biosolids (NB), old biosolids (OB), new biosolids with wood fines (NBWF) or old biosolids with wood fines (OBWF). Simulated rain events were equivalent to 31.8 mm rainfall, 350 mL of deionized water.

Leachate totals followed the same pattern for each SRE where NB > OB > NBWF > OBWF (Figure 4.6). New biosolids leachate totals were especially high as a result of SRE1 and SRE2 (172.4 mg and 104.5 mg, respectively), followed by OB (61.3 mg and 70.0 mg, respectively). However, OB ammonium losses were surpassed by NB organic-N losses (110 mg and 101 mg, respectively) as a result of the overall higher concentration of TN in the NB treatment. By SRE5, the NB ammonium leachate total remained higher than other treatments ($p < 0.001$), with a mean loss of 22 mg – 5× greater than any other treatment.

High ammonium losses from NB are attributed to the higher concentration of ammonium in NB (Table 4.1) as well as the higher concentration of organic-N that was available to mineralize over the course of the study. Ammonium losses were reduced in aged products since the analysis results suggest that much of the organic-N had mineralized during storage (as evident by the lower concentration of organic-N) and that net losses of ammonium to volatilization and nitrate to leaching had occurred (as evident by the lower concentration of TN). Net loss of N from OB likely are likely attributed to volatilization. Robinson and Polglase (2000) showed that volatilization of ammonium for surface applied biosolids was rapid – with most N being lost within the first week of application. Within three weeks, 71% – 81% of the ammonium applied had been lost. After that, changes in the ammonium concentration were small and there was little loss of organic N. Because the losses occurred so quickly, the authors concluded that volatilization was the primary mechanism for net N losses since denitrification involves slower biological processes. Furthermore, the authors suggested that volatilization of surface applied biosolids could be used as a method to protect ground water from nitrate pollution.

4.3.2.5 Total Nitrogen and Organic Nitrogen

Generally, ammonium was the dominant form of N in leachates for all treatments. Therefore, column study ammonium and TN trends were closely associated (Figure 4.6). Organic-N comprised 40%, 24%, 31%, and 20% of TN in NB, OB, NBWF, and OBWF leachates, respectively. The aged amendments, OB and OBWF, had 64% to 66% less organic-N, whereas the BWFs had 70% to 72% less. The pattern for organic-N cumulative leachate totals was similar to that of ammonium and TN, where NB > OB > NBWF > OBWF, except that OB and NBWF were statistically similar (Table 4.4). For the most part, organic-N losses diminished after each SRE (Figure 4.6). This is explained by previous leaching events and mineralization, which shrunk the organic-N pool. Diminishing TN totals are explained by previous SRE losses and unmeasured gaseous losses.

Aging reduced TN leachate losses by 40% and 47% for OB and OBWF, respectively while WF reduced losses by 60% and 65% for NBWF and OBWF, respectively. A Two-Way ANOVA could not be performed to test whether aging and WF interacted to effect leaching because the assumption of equal variances was violated. Therefore, independent sample t-tests were conducted to test the effects these variables had on cumulative totals. Aging was not shown to be statistically significant ($p = 0.054$), which could be attributed to the small sample size and high variance (4 replicates/treatment). However, wood fines was a significant factor [$t\ (9.74) = 5.92$, $p < 0.001$]. Paramashivam et al. (2016) noted similar findings and concluded that that sawdust mixed with biosolids physically sorbed both ammonium and nitrate, thereby reducing leaching losses. Especially noteworthy is that the NB SRE1 mass loss of TN was equivalent to 73% of the cumulative TN loss for OB and was greater than the cumulative mass losses for NBWF and OBWF. This finding demonstrates that unamended fresh biosolid materials have the potential to release high volumes of nitrogen as compared to aged biosolids or biosolids that are diluted with a filler product such as WF. The overall assessment of the column study N results is that aging and WF additions reduce N leaching; however, at the expense of the nitrogen content of the resulting products.

4.3.3 Greenhouse Study

4.3.3.1 Soil OM and pH

Each biosolids amendment increased soil OM when incorporated, with the highest increase noted in NBWF (Table 4.5). Ten weeks after seeding the microcosms, the OM% had increased in all treatments, including C and F. However, the results were highest in the treatments which received biosolids, especially with the fresh NB and NBWF.

The initial mean control soil pH was 6.48. Fertilizer had no effect on the initial pH of the soil. But all biosolids amendments significantly lowered soil pH, especially NBWF and NB, which were pH 5.75 and 5.8 respectively. After 10 weeks there was no difference between initial and final pH for C and F, but the mean for OBWF (6.55) was higher than the initial value (p = 0.006). Likewise, the final mean pH for NBWF (6.03) was higher than the initial value (p = 0.01). On the other hand, the mean pH for NB (5.15) had decreased further ($p < 0.001$).

The importance of this is that biosolid materials have different effects on soil pH depending on the wastewater treatment process and the subsequent availability of nutrients for plant uptake. Alkaline-stabilized biosolids, are known to raise soil pH (Sloan and Basta, 1995). However, anaerobically digested biosolids, such as the product used in this experiment, are known to lower it (McIvor et al., 2012; Dede et al., 2017). Sullivan et al. (2006), showed that pH was negatively correlated to the application rate of biosolids with results between 5.5 and 6.3 that were lower than the pH of the biosolids used in the experiment, i.e.,7.3. Here, the pH of the amendments for OBWF, NBWF, and NB were 7.8, 7.5, and 8.8. Decreases in soil pH following incorporation of these materials are not explained by the pH of the biosolids, but rather by the effects of nitrification. The effect was greater for NB because it had the highest concentration of NH_4^+ in the amendment. Non-traditional biosolids consumers should be made aware of the expected pH changes related to various biosolids products so that informed decisions can be made before purchase/use.

Table 4.5: Greenhouse microcosm study before (B) and after (A) soil analysis summary. Treatments included an unamended topsoil (C), a soil fertilized with a 20-16-12 ($N-P_2O_5-K_2O$) starter fertilizer (F) and soils amended with either new biosolids (N), old biosolids (OB), new biosolids and wood fines (NBWF), or old biosolids and wood fines (OBWF). Analyses conducted by Matrix Sciences are expressed as mean ± the SE. Where indicated with the inclusion of a p-value (α = 0.05), ANOVA was performed to determine if significant differences existed between treatments. Equality of variance was met for each analysis; therefore, the Bonferroni Correction was used for post-hoc analyses. Values in rows which have different letters are significantly different when α = 0.05 and F (4, 20) > 2.90.

Measurement	Time	C	F	OBWF	NBWF	NB	P Value
OM%	B	1.95 ± 0.09a	1.95 ± 0.03a	2.80 ± 0.06b	3.40 ± 0.21c	3.08 ± 0.07bc	< 0.001
	A	2.15 ± 0.05a	2.23 ± 0.25a	3.35 ± 0.09b	3.93 ± 0.02c	3.95 ± 0.03c	< 0.001
pH	B	6.48 ± 0.02c	6.48 ± 0.02c	6.20 ± 0.00b	5.75 ± 0.03a	5.80 ± 0.04a	< 0.001
	A	6.78 ± 0.03d	6.58 ± 0.25c	6.55 ± 0.05c	6.03 ± 0.25b	5.15 ± 0.03a	< 0.001
NO_3-N (ppm)	B	9 ± 2a	12 ± 3a	35 ± 3b	107 ± 7c	126 ± 5.5d	< 0.001
	A	0.25 ± 0.05a	1.53 ± 1.39a	2.83 ± 0.58a	21 ± 2a	140 ± 17b	< 0.001
NH_4-N (ppm)	B	1.43 ± 0.22a	35.15± 3.13c	3.00 ± 0.43a	22.18 ± 2.46b	90.73 ± 1.1d	< 0.001
	A	4.05 ± 0.20a	3.73 ± 0.26a	4.60 ± 0.19a	6.05 ± 0.36b	6.65 ± 0.40b	< 0.001
PSR*	B	23 ± 0.6a	32 ± 1.5b	42 ± 0.4c	43 ±1.9c	49 ± 1.5d	< 0.001
	A	24 ± 0.4a	30 + 1b	53 ± 1c	59 ± 1d	70 + 1c	< 0.001
M3P (ppm)	B	70 ± 1.3a	101 ± 6.4b	140 ± 3.5c	146 ± 9c	156 ± 8c	< 0.001
	A	75 ± 1.5a	101 ± 3b	180 ± 6c	230 ± 2.6d	278 ± 5c	< 0.001
Ca (ppm)	B	741 ± 20a	719 ± 16a	1056 ± 42b	1243 ± 45c	1164 ± 22bc	< 0.001
	A	926 ± 9a	911 ± 9a	1275 ± 26b	1339 ± 41b	1300 ± 71b	< 0.001
Fe (ppm)	B	460 ± 9a	455± 6a	493 ± 8.5a	585 ± 15b	600 ± 26b	< 0.001
	A	490 ± 7a	503 ± 2.5a	568 ± 4.8b	735 ± 5c	923 ± 14d	< 0.001
Al (ppm)	B	565 ± 21c	545 ± 3bc	515 ± 13b	520 ± 4b	438 ± 15a	< 0.001
	A	562 ± 2.5cd	573 ± 7.5d	498 ± 11b	528 ± 11bc	440 ± 7a	< 0.001

* The Phosphorus Saturation Ratio is based on Mehlich-3 extractions. Results are interpreted as followed: < 25 – low-medium risk; 25-50 – high risk; > 50 – very high risk.

4.3.3.2 Phosphorus

All treatments increased extractable-P (M3P) as well as the phosphorus saturation ratio (PSR) above the control; but NB, NBWF, and OB had larger differences than F (Table 4.5). By the end of the experiment, saturation ratios (an important measure of solubility) had risen above initial results for all biosolids treatments but not for the C and F treatments. Likewise, M3P was relatively unchanged for the C and F treatments after 10 weeks. However, it was higher for OBWF, NBWF and NB. By the end of the study respective M3P was 61%, 70%, and 75% higher than the initial result for C. Additionally, respective PSR increases were 2.3, 2.6 and 3.0 times higher than the initial C result.

These results indicate that all treatments increased agronomic-P, especially the three biosolids treatments, since M3P is positively correlated with plant available P (Sims et al., 2002). The results also imply that the risk for P transport was higher for treated soils, since PSR is positively correlated with P transport (Nair, 2014). Given these results, the greatest P losses were expected to come from the NB treatment, followed by NBWF and OBWF. However, that was not the case. Cumulative TP leachate totals were 33.34 mg, 15.09 mg, 12.24 mg, 7.76 mg, and 6.88 mg for F, NB, C, OBWF, and NBWF respectively. The highest cumulative TP leachate total, attributed to the F treatment, was 2× higher than the mean for NB (Table 4.6).

Table 4.6: Greenhouse Study cumulative leachate losses for nitrate/nitrite (NOx), ammonium ($NH4^+$), total nitrogen (TN), orthophosphate (Ortho P), and total phosphorus (TP). Treatments included a control soil (C), soil fertilized with a 20-16-12 (N-P_2O_5-K_2O) starter fertilizer (F), and soil amended with either new biosolids (NB), NB with wood fines (NBWF) or two-year old biosolids with wood fines (OBWF). Tap water (TAP) was used for simulated rain events. Cumulative nitrogen and phosphorus additions from TAP are included. Values in rows which have different letters are significantly different ($\alpha = 0.05$), as determined by ANOVA ($p < 0.001$). The Games-Howell post hoc test was used for pairwise comparisons due to unequal variance.

Measurement		**C**	**F**	**OBWF**	**NBWF**	**NB**	**TAP***
$NH4^+$ (mg)	Mean	2.17a	75.90c	5.01b	92.32c	1,528.01d	0.00
	SE	0.35	6.56	0.58	15.27	151.83	
NOx (mg)	Mean	67.31a	97.87a	350.01b	1,831.03ab	13,781.40c	33.62
	SE	14.72	22.89	25.99	550.42	1,382.20	
TN (mg)	Mean	90.30a	268.59b	384.65b	2,557.87ab	16,802.55c	74.24
	SE	13.88	33.28	30.34	715.20	1,622.90	
Ortho P (mg)	Mean	3.96bc	18.07bc	3.57b	2.04a	3.64ab	10.45
	SE	0.31	2.89	0.11	0.18	0.56	
TP (mg)	Mean	12.24a	33.34b	7.76a	6.88a	15.09ab	12.06
	SE	1.22	4.10	0.64	0.42	2.54	

* Not included in statistical analyses because n=1.

Similar findings have been documented when soils treated with biosolids are compared to soils treated with phosphorus fertilizers (Lee et al., 1981; Favaretto et al., 2012; Andersson et al., 2016). Here, higher retention in NB despite higher M3P and PSR results could be explained by the higher Fe content (as already discussed) as well as higher Ca concentrations. Numerous studies have shown that exchangeable Ca^{2+} reduces P leaching, especially particulate-P (Favaretto et al., 2012; Andersson et al., 2016). The majority of TP in the F treatment was lost during SRE1, while losses from the other treatments were more constant (Figure 4.7).

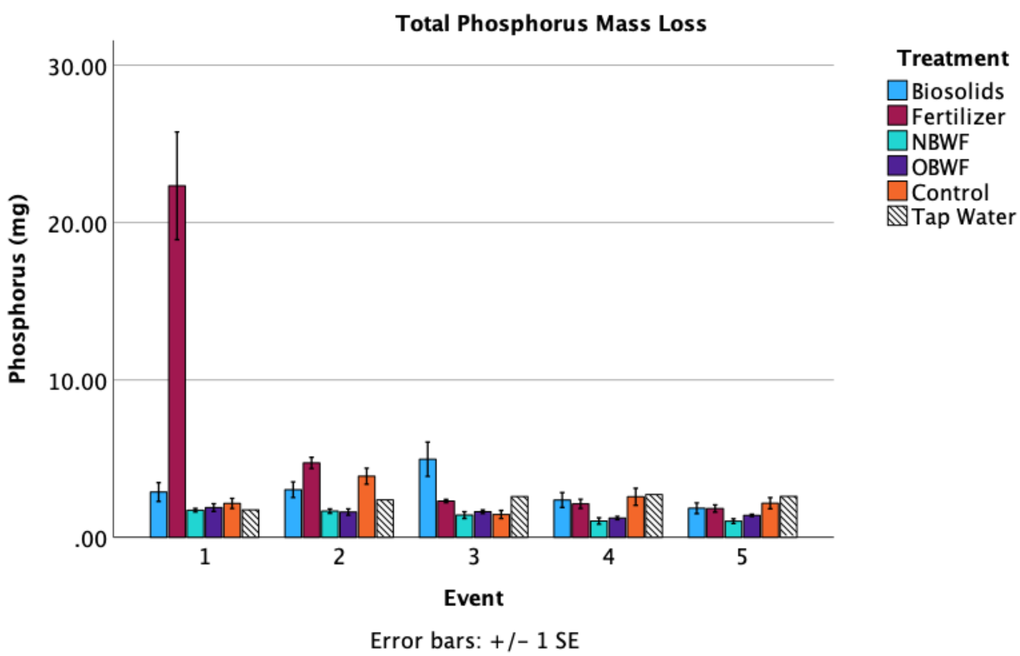


Figure 4.7. Greenhouse study total phosphorus (TP) leachate totals by treatment and simulated rain event. Treatments included: control (C), fertilizer (F), new biosolids (NB), old biosolids with wood fines (OBWF), and new biosolids with wood fines (NBWF). Hashed bars represent the tap water used to simulate rain. Simulated rain events were equivalent to a 25.4 mm rainfall, 8,720 mL of deionized water.

The results furthermore showed that despite high P loading rates to soil, OBWF and NBWF sequestered incoming P for the duration of the experiment. The tap water used for the SREs added a total of 12.06 mg of TP, mostly in the form of Ortho P. By SRE4, all treatments sequestered incoming P. By SRE2, all Ortho P losses were less than the amount of incoming Ortho P (Figure 4.8). Orthophosphates comprised < 50% of cumulative TP losses for each treatment, except F (Table 4.6).

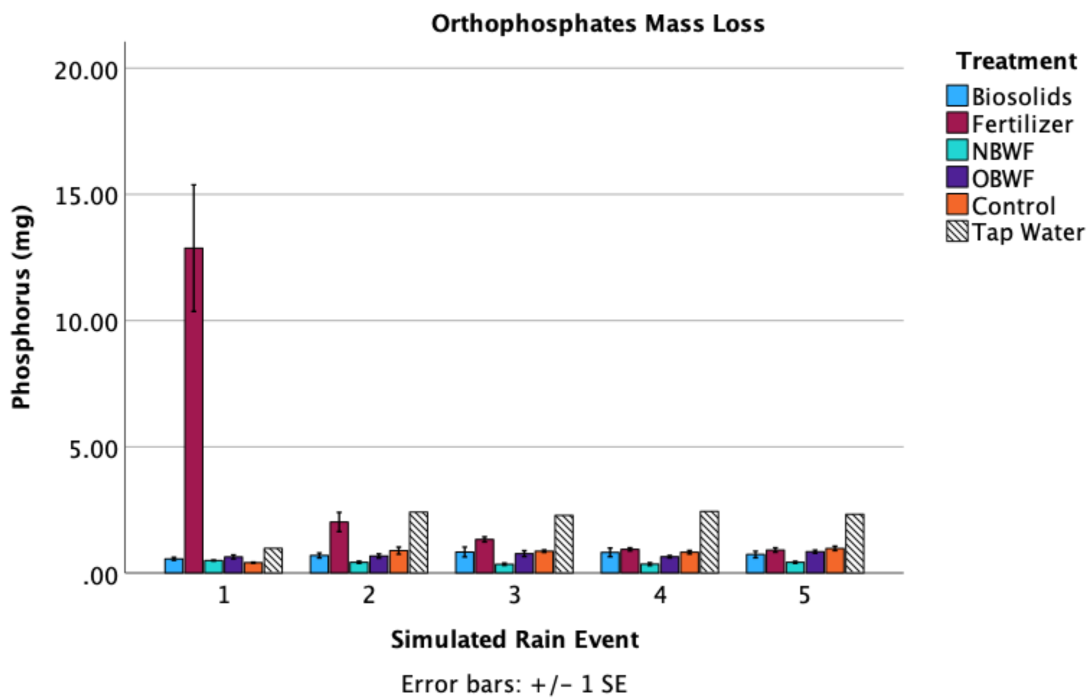


Figure 4.8. Greenhouse study leachate totals for orthophosphates by treatment and simulated rain event. Treatments included: control (C), fertilizer (F), new biosolids (NB), old biosolids with wood fines (OBWF), and new biosolids with wood fines (NBWF). Hashed bars represent nutrients additions to replicates from the tap water used to simulate rain. Simulated rain events were equivalent to a 25.4 mm rainfall, 8,720 mL of deionized water.

These results provide some assurance that pure biosolids and BWF co-amendments applied above N-agronomic rates do not increase the risk of P pollution, relative to mineral fertilizers, when added to soil with a low risk of P leaching as determined by the PSR. However, this study should be repeated on soil with higher PSR values to determine if biosolid P remains stable when applied over an area at 2.54 cm.

4.3.3.3 Nitrogen

The fertilizer used in this study was applied at 45 kg-N·ha^{-1}, in accordance with current MD recommendations for turfgrass establishment (Carroll and Turner, 2016). According to the amendment analysis, the biosolids amendments provided between 1123 and 2350 kg-N·ha^{-1} (Table 4.3). Of that 153, 131, and 128 kg·ha^{-1} were in the form of nitrate and ammonium at the time of incorporation for OBWF, NBWF and NB, respectively. The remaining 86%, 89%, and 95%, respectively, was organic-N. Therefore, plant available nitrogen (PAN) at the time of incorporation exceeded the agronomic-N rate for turfgrass establishment more than 2.8× for the biosolids amendments before factoring in first year mineralization rates. Soil tests showed that the initial PAN concentrations (ppm) were 10.43, 47.15, 45.00, 129.18, 216.73 or C, F, OBWF, NBWF, and NB, respectively (Table 4.5). After ten weeks of growth and five 25.4 mm SREs, the results demonstrated that nitrate and ammonium soil concentrations were similar for the C, F, and OBWF treatments. However, N concentrations for NBWF and NB were still above control concentrations. These results imply that 1) all treatments should increase N leaching, and 2) losses should be greater from the biosolids treatments, especially NBWF and NB.

Nitrogen leaching predictions were confirmed by the test results. Mass losses for N leachate were highest for NB > NBWF > OBWF = F > C (Table 4.6). Unlike the column study where the majority of TN was leached as ammonium, the greenhouse microcosm leachates were dominated by NOx (Figure 4.9). The cumulative TN leachate mass loss total for NB was 63× more than the total for F. Total N and NOx leaching rates are summarized in Table 4.7.

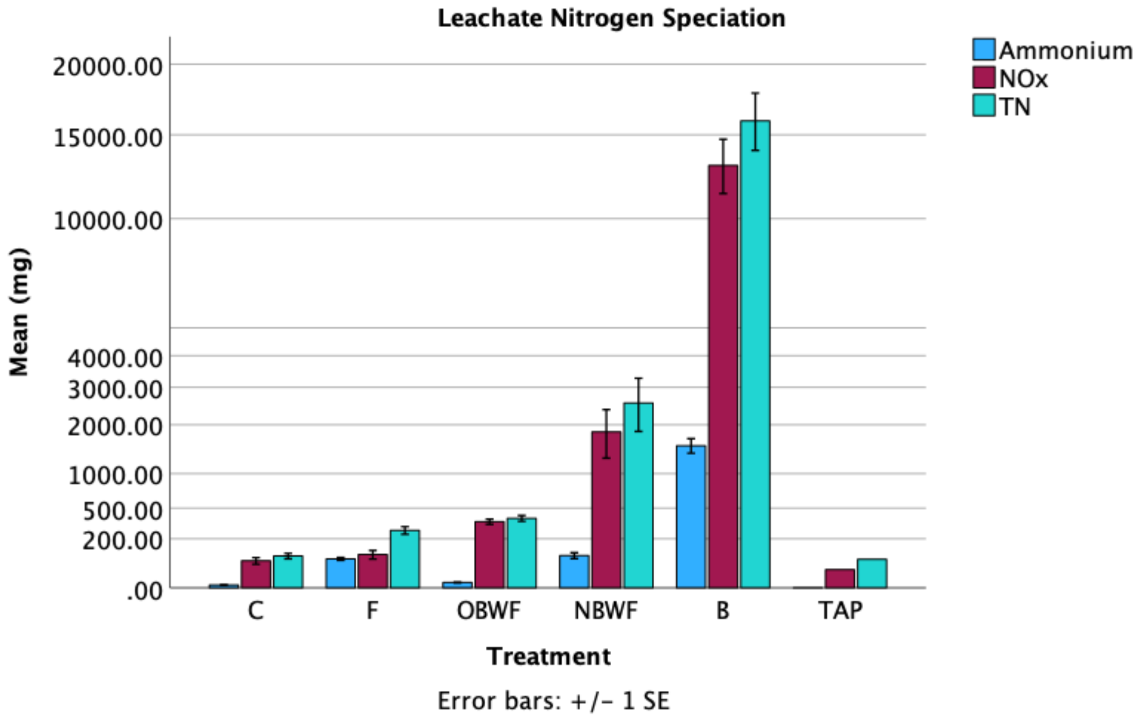


Figure 4.9. Nitrogen speciation for the greenhouse study cumulative leachate mass losses by treatment. Treatments included a control soil (C), soil treated with a fertilizer (F) or soil amended with either new biosolids (NB), new biosolids with wood fines (NBWF) or old biosolids with wood fines (OBWF). Leachate was collected from five simulated rain events, each equivalent to a 25.4 mm rainfall (8,720 mL). Nutrient additions from the Tap water used to simulate rainwater are included.

Table 4.7: Greenhouse study application and leaching rates for total nitrogen (TN) and nitrate + nitrite (NOx). Treatments included: control (C), fertilizer (F), new biosolids (NB), old biosolids with wood fines (OBWF), and new biosolids with wood fines (NBWF).

Treatment	TN applied kg-N·ha^{-1}	TN leached kg-N·ha^{-1}	NOx leached kg-NOx·ha^{-1}
C	0	2	2
F	45	7	3
OBWF	1123	10	9
NBWF	1196	68	49
NB	2350	445	365

Results show that the majority of TN lost from the F and OBWF treatments was leached during the first 50.8 mm of simulated rain (Figure 4.10). By SRE3, C, F, and OBWF leachate mass loss totals were similar. On the other hand, NBWF and NB losses peaked during SRE2 and SRE3. By SRE5, TN losses were sill 20× and 208× higher than C losses for NBWF and NB, respectively. Trajectories for NBWF and NB show that the rate of loss was diminishing after SRE3. Even so, it's clear from the greenhouse study data that several more significant rainfall events would be needed before NBWF and NB TN and NOx leaching losses were equivalent to the control losses (Figure 4.11). The column study supports this assumption since NB and NBWF NOx losses had become more steady state by SRE3, which persisted by SRE5 (Figure 4.5).

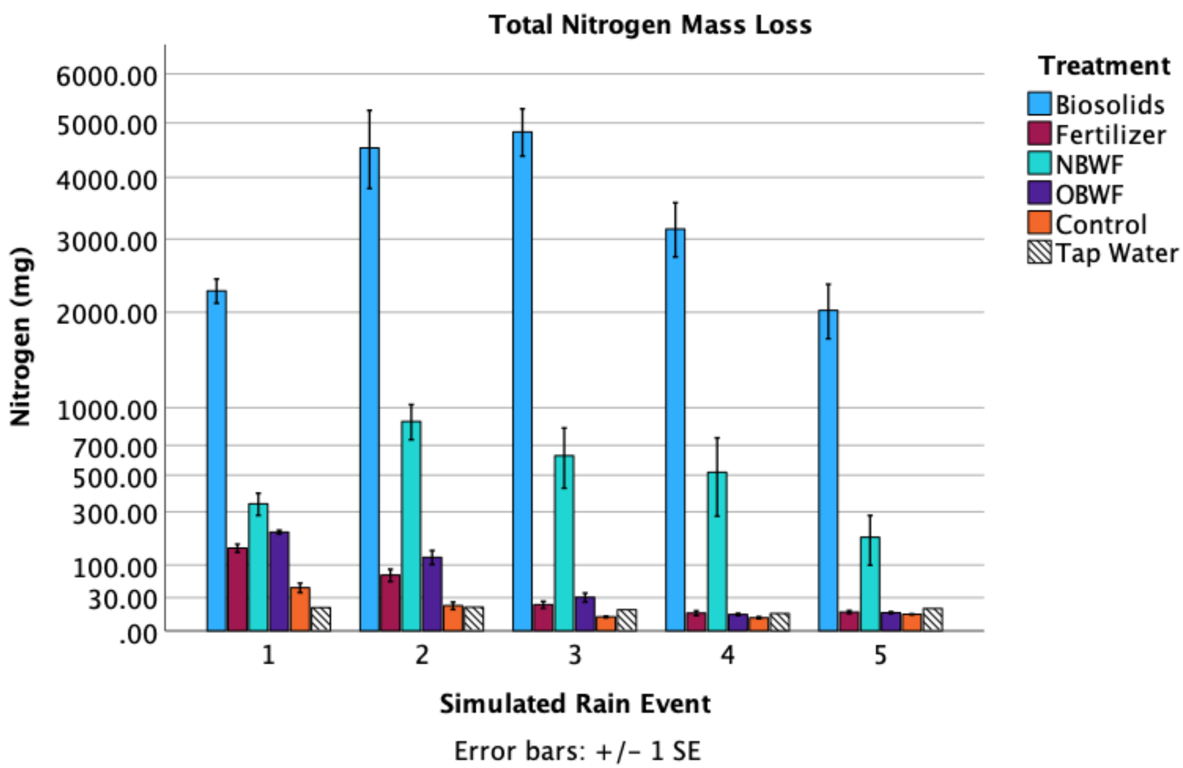


Figure 4.10. Greenhouse study Total Nitrogen mass losses by treatment and simulated rain event. Treatments included a control soil (C), soil treated with a fertilizer (F) or soil amended with either biosolids (NB), new biosolids with wood fines (NBWF) or old biosolids with wood fines (OBWF). Hashed bars represent associated nutrient additions to microcosms from the tap water used to simulate rain. Simulated rain events were equivalent to a 25.4 mm rainfall, 8,720 mL of deionized water.

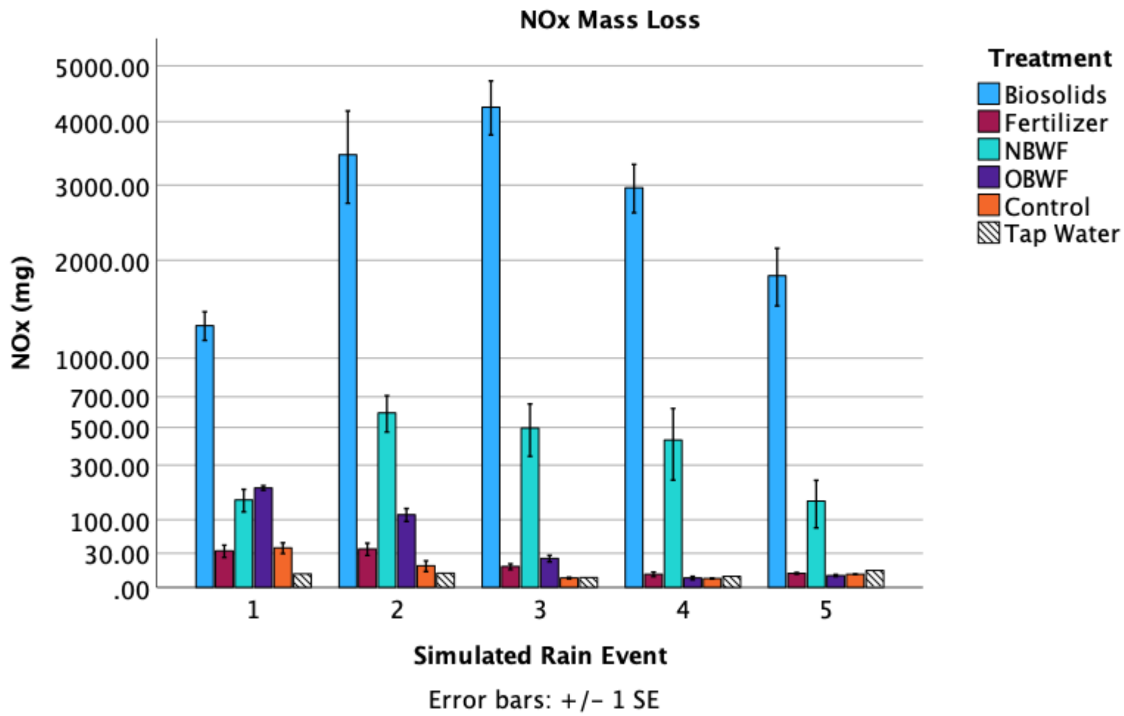


Figure 4.11. Greenhouse study nitrate/nitrite (NOx) leachate mass losses by treatment and simulated rain event. Treatments included a control soil (C), soil treated with a fertilizer (F) or soil amended with either biosolids (NB), new biosolids with wood fines (NBWF) or old biosolids with wood fines (OBWF). Hashed bars represent associated nutrient additions to microcosms from the tap water used to simulate rain. Simulated rain events were equivalent to a 25.4 mm rainfall, 8,720 mL of deionized water.

To put these findings into perspective, results were compared to results from a similar experiment in which nitrate leaching from the root zone of soil amended with biosolids and biosolids/saw dust co-amendments were applied at one to seven times N agronomic rates (Daniels et al., 2003). In that study, nitrate leachate mass losses collected over a two-year period range from 6 - 60 $kg \cdot ha^{-1}$. Here, NOx leachate mass losses were equivalent to 365 $kg \cdot ha^{-1}$ for the NB treatment. Confined by microcosm walls, simulated rain was forced to leach through the soil profile. In a natural setting, unabsorbed rain would probably become surface runoff. Therefore, leachate volumes and subsequent mass losses were likely higher than they would have been in a natural setting. Even so, these results raise concerns about N losses when 2.54 cm of NBWF and NB are applied.

4.4 Conclusions

Aging and wood fines had significant impacts on the nutrient content of the biosolid material used in this study as well as the potential to retain and leach N and P. While WF decreased the concentration of most amendment nutrients, aging only decreased the concentration of N and a few micronutrients (Fe, Zn, and Cu) – not P. Net N losses are inevitable in open storage systems due to gaseous and leaching losses, which are replaced by mineralized N. Therefore, long term storage decreased the N fertilizer value of biosolids because organic-N was reduced in aged biosolids. This meant that the N value for the two-year old product used in this study was similar to air-dried biosolids, which generally have lower fertilizer values than comparable mechanically dewatered products. Even though the overall concentration of TP in new and old biosolid material was similar, the concentration of mineral P was higher in the aged product. Because P mineralization is affected by moisture, it would be helpful for future studies to investigate how storage practices, such as open-air stockpiling, affects P speciation in commercially available biosolids products.

Wood fines and aging had similar impacts on the TN value of fresh biosolids, with reductions equal to about 25%. However, the impact of WF on TP was greater (reduced by 56%) when mixed at a 1:1 ratio. The implication for these findings is that users and secondary dealers should be made aware that nutrient contents for biosolids will diminish over time or with the addition of wood fillers. New users should also be made aware that high pH biosolids will likely lower soil pH, especially those newer products with high mineralization potentials. This study was conducted on two-year-old anaerobically digested, mechanically de-watered biosolids. It should be repeated with products produced by different processes and with different ages to better inform potential users.

Based on ammonium and nitrate concentrations alone, 2.54 cm of NB, OB, NBWF and OBWF surface-applied on land will greatly exceed N recommendations for turfgrass establishment and will result in higher leachate mass loss totals than from soil treated with a high efficiency fertilizer applied at the appropriate N-agronomic rate. Leachate mass losses for TN were highest for NB > NBWF > OBWF = F > Control. The cumulative TN leachate mass total for NB was 63× more than the total for fertilized soil. The magnitude of the difference is expected to be higher with additional simulated rainfall events since NB TN mass totals were still declining after 127 mm was applied. Generally, ammonium was the dominant form of N in all column study leachates. However, once the amendments were incorporated into soil, nitrate was the dominant N species due to rapid microbial nitrification. The majority of TN lost from the F and OBWF treatments was leached during the first 50.8 mm of simulated rain. However, high losses persisted longer for NBWF and NB. By the fifth simulated rain even, TN losses were sill 20× and 208× higher than losses from the control for NBWF and NB, respectively. These results demonstrate that 2.54 cm of NB and NBWF spread over the landscape poses a significant risk for N losses to groundwater, for an extended time.

The amendment analysis showed that total P will be in excess when 2.54 cm of NB, OB, NBWF, and OBWF are surface applied to land. However, much of the P contained in these amendments will likely not be plant-available due to the Fe and Ca compounds added during the treatment process. These compounds should help to retain P in soil with low PSR values, despite significant rises in TP, M3P, and PSR values. Wood fines helped to further reduce TP transport from fresh biosolids when mixed at a 1:1 ratio. Altogether, the results from this study provide some assurance that pure biosolids and biosolid/wood fine co-amendments applied above N-agronomic rates will not result in high impact waterborne P pollution when added to soil with a low risk of P leaching as determined by the PSR. However, this study should be repeated on soil with higher PSR values to determine if biosolid P remains stable when applied at the same rate. Additionally, users should be advised to monitor soil P availability if biosolids are applied at high agronomic N rates - especially when applying maintenance fertilizers as any additional P inputs will be at a higher risk of transport.

Use of biosolids in landscapes and home gardens is poised to grow due to economic factors, efforts to increase sustainability, and increased accessibility to EPA Class A EQ biosolids. Considering the amount of land available to receive such products and the collective potential for various products to contribute to non-point source N pollution, attention should be paid to strategies that reduce valuable nutrient losses. This study confirms that aging and wood fines reduce waterborne N pollution from biosolids – though at the expense of losing nitrogen.

Chapter 5: Policy and technology assessment for biosolid amendments used in manufactured topsoils and landscaping activities

5.1 Introduction

The Chesapeake Bay is the largest, most productive estuary in the US, and provides immeasurable values to the Nation (Morgan and Owens, 2001). For decades, excess sediment and nutrients from agricultural and urban sources, primarily nitrogen (N) and phosphorus (P), have significantly impacted the bay's health. These nutrients, along with potassium (K), are essential to plants and are the main ingredients in most commercial fertilizers. However, if applied at the wrong time, in the wrong manner, or in quantities that exceed plant needs, solubilized and particulate bound N and P can transfer to waterways through runoff from excess irrigation and rainwater. Eutrophication results from waterways enriched with N and P. The Chesapeake Bay Program estimated that agriculture, followed by developed land, then wastewater were the three largest non-natural sources of N and P pollution between 1985 and 2022 (Chesapeake Progress, 2023). To address such non-point sources of N and P pollution, Maryland's Nutrient Management Program (NMP) imposes requirements and restrictions on farmers, lawn care professionals, and even homeowners to prevent excess nutrients from non-point source pollution from entering the Bay.

The Maryland Department of Agriculture (MDA) with help from the University of Maryland Extension (UME) established the Maryland Nutrient Management Program in 1989 to help farmers voluntarily reduce non-point source nutrient pollution by reducing fertilizer rates and more precisely timing and placing fertilizers. A decade later, the Maryland Water Quality Improvement Act (WQIA) was passed, which regulated commercial fertilizer applications on non-agricultural land. Additionally, the WQIA established turfgrass fertilizer requirements that are based on University of Maryland guidelines. Then, in 2009, the Chesapeake Bay Phosphorus Reduction Act was passed, which restricted the P content of turfgrass fertilizer and imposed requirements on manufacturers selling fertilizer in Maryland.

Soon after passage of the Chesapeake Bay Phosphorus Reduction Act of 2009, members of the Chesapeake Bay Commission introduced legislation to reduce pollution from lawn fertilizers applied to homes, golf courses, and businesses. Subsequently, the Fertilizer Use Act of 2011 was signed into law on May 19, 2011 by Maryland Governor O'Malley. This law stands today (amended) and pertains to anyone who fertilizes non-agricultural turf, including homeowners by restricting the amount of N and P that can be applied as well as the dates for fertilizer applications. Notably, the law applies to fertilizers as well as organic sources of N and P in order to curb non-point source pollution from urban sources.

The intent of Maryland's fertilizer law is to help homeowners and lawn care professionals maintain healthy lawns without applying unnecessary N and P. It is written in a way that requires the Maryland Department of Agriculture (MDA) to consult with the University Maryland (UMD) to develop a public education program, soil testing guidelines, and fertilizer recommendations (MD Code, Agriculture §8–803.7). Additionally, UMD is required to review turf fertilizer recommendations every three years and revise them as necessary, with consideration of plant nutrient requirements. The current recommendations are summarized in UMD Turfgrass Technical Update TT116 for turfgrass establishment (Carroll and Turner, 2016) and TT115 for commercially maintained lawns and turfgrass (Turner, 2013). University of Maryland recommendations carefully balance the need to provide enough plant nutrition to support rapid establishment of turf to reduce erosion losses, and associated N and P mobilization, while also restraining overapplication of nutrients to prevent unnecessary losses. For this reason, recommendations for turf maintenance are stricter than recommendations for turf establishment. Research supports this, since nutrients in natural ecosystems such as grasslands cycle through a continuous circle of uptake, immobilization and mineralization (Woodmansee et al., 1981). Booze-Daniels et al. (2000) recommends fertilization of N, P, and K at establishment and every three to five years to maintain adequate density of pure grass stands. Otherwise, nutrient cycling is relied upon for long-term fertility of mixed stands.

As noted previously, these application restrictions apply to composts and natural organic fertilizers. New regulations went into effect in 2018 that made regulations for organic fertilizer products consistent with synthetic products. However, restrictions are based on the method of application. If organic products are surface applied, they are treated like fertilizers and are subject to the N and P restrictions described below. Nutrient content of such products is determined based on the results of a current (< 12 months) nutrient analysis. However, if organic products are *incorporated* into at least 6 inches (15.24 cm) of soil, a 1-inch (2.54 cm) application is allowed (based on UMD's current recommendation), regardless of the product being applied. Organic products that are incorporated do not need a nutrient analysis since N or P content is not restricted under these circumstances.

Current *fertilizer* restrictions for turfgrass *establishment* include the following:

- Everyone must follow UMD fertilizer application recommendations.
- Homeowners shall not apply fertilizers (including surface applied organic fertilizers) between November 16 and March 1. Applications by certified professional landscapers are restricted between December 1 and March 1.
- Fertilizer shall not be applied within 15 feet of waterways, if heavy rain is predicted, or if the ground is frozen.

- A single application shall not exceed 44 kg $N \cdot ha^{-1}$, of which soluble N shall not exceed 34 kg $N \cdot ha^{-1}$. An approved enhanced efficiency N fertilizer that releases < 34 kg $N \cdot ha^{-1}$ per month can be applied to a seedbed/area to be sodded at a rate of 122 kg $N \cdot ha^{-1}$. However, it must not exceed 80% of the total annual N rate recommended for maintenance of the turfgrass species used. (Note: The UMD recommendation for 1-2 years after establishment for tall fescue is 122 – 171 kg $N \cdot ha^{-1}$ and 146 – 195 kg $N \cdot ha^{-1}$ for Kentucky bluegrass).
- A soil test is recommended but not required for P applications. (Note: A test must be conducted before applying maintenance P. Maintenance rates are determined based on P soil test results, discussed below).

To comply with the requirements described in §8–803.7, UMD formulated specific equations for participating labs that convert soil test results into unitless "fertility index values" (FIV), regardless of the test methods used. This way, results from any approved laboratory can be compared to ranges that describe the likelihood of yield responses should the soil receive a phosphorus fertilizer. Soil test categories range from *low* (0 – 25, yield response likely) to *excessive* (>100, yield response very unlikely). Fertility index value categories, including associated P restrictions for broadcast and incorporated materials, are summarized in Appendix E.

Results from Chapter 3 showed that the properties and nutrient content of organic amendments (mulch, compost and biosolids) can be quite different and lead to different yield outcomes when incorporated into soil at similar rates. Chapter 4 then showed that biosolid products made by the same manufacturer can have very different nutrient values depending on what other products (if any) are incorporated with them. Additionally, the results in Chapter 4 showed that the age of biosolids affects N values. Finally, Chapter 4 demonstrated that some biosolids products have the potential to release heavy N loads for a prolonged period when used at the current UMD turfgrass recommendation rate for organic products.

These prior study results therefore justify asking the following questions. 1) How does 2.54 cm of biosolids incorporated into soil affect turfgrass establishment in comparison to a fertilizer applied at the rate recommended by UMD for turfgrass establishment? 2) Do growth improvements, if they occur, justify high nutrient losses from biosolids?

5.1.1 Research Objectives

The objectives of this final study were therefore to:

1. Measure the effects of 3 biosolid treatments and a control fertilizer on the growth responses (dry mass, height, coverage, and N and P uptake) of replicate field turf plots.
2. Measure treatment effects on soil fertility before and after two growing seasons to determine if effects persisted after turf establishment.
3. Measure the quantity of N assimilated into (above ground) biomass and compare these results to measured leachate losses to assess if there were differences in the efficiency of nutrient applications.
4. Evaluate the current UMD organic amendment recommendation for turfgrass establishment as it pertains to biosolids for the purpose of improving nutrient management guidelines, if necessary.

5.2 Materials and Methods

5.2.1 Research Sites and Treatments

This research included the growth results of two studies: a nine-week greenhouse microcosm study (GHS) and an eight-month field study (FS). Treatments included a control soil (C), soil fertilized with a 20-16-12 (N-P_2O_5-K_2O) slow-release fertilizer (Growmark FS, LLC, East Berlin), and soil amended with either fresh biosolids (NB), a 1:1 (v:v) blend of fresh biosolids and wood fines (NBWF), or a 1:1 (v:v) blend of two-year old biosolids and wood fines

(OBWF). Given its availability throughout Maryland, Fresh Bloom® (Blue Plains WWTP, Washington, DC), a Class A EQ biosolids product produced through thermal hydrolysis and anaerobic digestion was selected for the three biosolids amendments.

Fresh Bloom® was sourced directly from the production line for use in these experiments. Two-year-old Fresh Bloom® and hard wood fines were acquired from Grant County Mulch (Laurel, Maryland), where the products were stored in non-covered stockpiles. The wood fines selected for this study were the same used in the Bloom Woody Blend®. They had a consistency similar to sawdust and were ground from woody debris sourced from land clearing activities, sawmills, and landscapers (Figure 5.1). Blended amendments (NBWF and OBWF) were mixed at UMD just prior to use. The properties of the biosolid blends and their components were described in Chapter 4.

Figure 5.1. Recycled wood fines (WF) were blended 1:1 with old biosolids to form the OBWF amendment. Likewise, they were blended with fresh biosolids to form the NBWF amendment

The fertilizer selected for these experiments is used for turfgrass establishment on Maryland highway embankments and is characteristic of starter fertilizers that homeowners might select for home use in Maryland. University of Maryland recommendations for turfgrass establishment were implemented for the Fertilizer (F) treatment, which allowed for 224 kg·ha^{-1} of the fertilizer to be applied to the GHS microcosms and FS plots. Biosolid amendments were applied "as is" to a depth of 2.54 cm and incorporated into 10.16 cm of soil, 5.08 cm shy of the 15.24 recommended depth. The depth of incorporation was based on the depth of penetration for the tiller used to incorporate amendments (Barreto; LaGrande, OR). Nitrogen and phosphorus loading rates for each treatment are summarized in Table 5.1.

Table 5.1: Total nitrogen (TN), soluble nitrogen (NH_4^+ & NO_3^-), organic-N, and phosphorus (expressed as P_2O_5) loading rates based on treatment application rates. Treatments included three biosolids amendments (new biosolids (NB), NB with wood fines (NBWF) and OB with wood fines (OBWF)) and a 20-16-12 (N-P_2O_5-K_2O) slow-release fertilizer containing 11.6% water insoluble N as ureaform. Amendments were applied to a depth of 2.54 cm before incorporation into 10.16 cm of soil. The rate used for the F treatment was 224 kg·ha^{-1}.

Treatment:	Application rate	TN kg·ha^{-1}	NH_4^+ & NO_3^- kg·ha^{-1}	Organic-N kg·ha^{-1}	P_2O_5 kg·ha^{-1}
NB	171 Mg·ha^{-1}	2,350	128	2,222	3,495
NBWF	114 Mg·ha^{-1}	1,196	131	1,059	1,020
OBWF	122 Mg·ha^{-1}	1,123	153	970	1,367
F*	224 kg·ha^{-1}	45			36

* 3.38% ammoniacal N, 5% water soluble N, and 11.62 water insoluble N

5.2.2 Field Study

The field study was conducted at UMD's Paintbranch Turfgrass Research Facility located in College Park, MD. Soil at the facility is classified by the United States Department of Agriculture as an RcA Russett-Christiana complex (0-2% slope), which is a fine-loamy, mixed, semiactive, mesic Aquic Hapludults. In July 2022, a 15 m × 15 m area was sprayed with a glyphosate-based herbicide (Roundup, Bayer USA; Whippany, NJ) to kill existing turf. Eight weeks later, the area was tilled to a depth 15.88 cm with a Rotodairon 150 Soil Renovator (Salem, OR) to mimic disturbed bare soil.

Field plots (1.52 m^2) with walkways (0.91 m) were arranged in a Latin square design (Figure 5.2). On September 15, 2022, the three biosolids treatments were tilled into respective plots with a rear-tine tiller. After the amendments were incorporated, the entire research area was rolled (610 lbs Gas Greens Roller, Model 09060, Salsco, Inc., Cheshire, CT) to prevent the amendments from washing away during rainstorms capable of producing sheet flow.

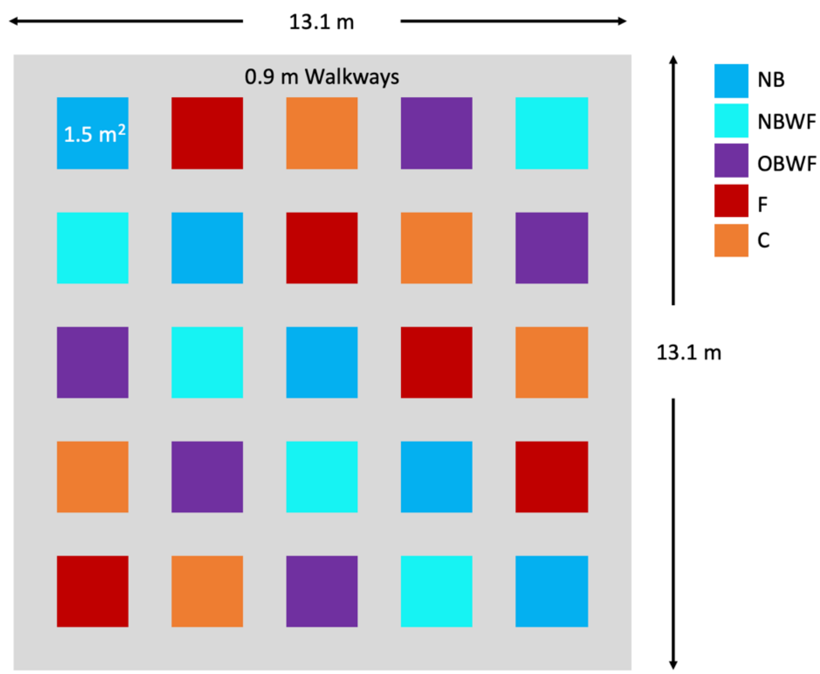


Figure 5.2. Field study experimental design. Treatments were arranged in a Latin square and included an unamended control soil (C), soil treated with a fertilizer (F), and soil amended with either fresh biosolids (NB), NB and wood fines (NBWF) or old biosolids and wood fines (OBWF).

Soil sensors and a data logger (Em50®, Meter Group, Inc., Pullman, WA) were installed in three plots of every treatment to monitor volumetric water content (GS1 and TEROS 12 sensors, Meter Group, Inc., Pullman, WA) and temperature (TEROS 12). Sensors were buried 5 cm below the surface. The arrangement of the sensors and data logger are depicted in Figure 5.3. Measurements were recorded every 15 minutes. The average daily minimum volumetric water content was determined for each plot after removing records from malfunctioning sensors (1 OBWF GS1, 1 NB GS1, and 1 NB Teros 12). Treatment averages were then based on plot averages. Results from May 20 -26, 2023 are reported. The average daily low and high temperature for the days observed were 10°C and 25°C; and 3.3 mm of rain was reported on the first day of observation.

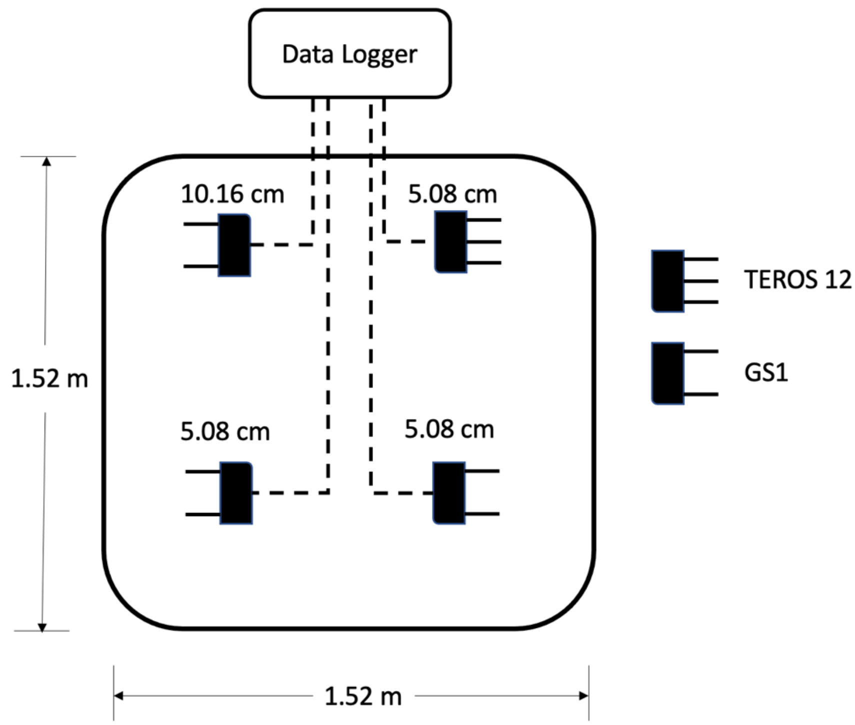


Figure 5.3. Soil sensor and data logger schematic for the field study plots. Each plot (3/treatment) was fitted with three GS1 sensors to measure soil moisture and one TEROS 12 to measure soil moisture and temperature.

On September 27, 2022, the plots were seeded (224 kg·ha^{-1}) with a cool season turfgrass mix (Chesapeake Valley Seed; Savage, MD). The mix consisted of two tall fescue cultivars and one Kentucky Bluegrass: *Festuca arundinacea* 'Wichita' (49.69%), *Festuca arundinacea* 'Gold

Medallion' (44.76%) and *Poa pratensis* 'Wild Horse' (4.98%). On the same day, fertilizer was surface applied to plots receiving the F treatments. Plots were rolled a second time to ensure good seed/soil contact. They were then watered with an overhead sprinkler for 30 minutes a day for the next three days, before being covered with a germination blanket. This was done to protect the seed from washing away due to the remnants of a tropical storm. The germination blanket was removed on October 8, 2022 after 2.54 cm of shoot growth was observed. To suppress weeds, an herbicide (Meso 4 SC Select, Prime Source LLC; Middlesex, NC) was applied one month later on all plots and walkways at the rate recommended for post-emergence applications (0.0366 $mL·m^{-2}$).

On November 11, 2023, seven weeks after seeding, mean shoot height was determined by measuring the length of 10 randomly selected primary shoots from each replicate plot. A ruler was used to measure from the base of the crown to the tip of the shoot. After recording height measurements, plots were then mowed to 7.62 cm (3 inches). Clippings were placed in paper bags and dried at 50°C. After 72 hr, shoot dry mass was recorded. Dry shoot mass was sent to Matrix Sciences (Harrington, DE) for analysis of leaf tissue nutrient content. There, N was assessed via combustion (Horneck and Miller, 2019) and the remaining nutrients were assessed using ICP after plant tissue was digested (Huang and Schulte, 1985). Plots were not mowed again until the following spring. Thereafter at each mowing (7 total), grass clippings were bagged, dried, weighed, and sent for tissue analysis. After the biosolid amendments were incorporated in September 2022, amended soil samples were collected and thereafter every three months until the first week of June, 2023 (4 times total). At each sampling, five soil cores were taken with a core sampler (10.16 cm; 4" depth) from each plot, then pooled and mixed thoroughly for sample analysis (n = 25 in total). Soil samples were analyzed by Matrix Sciences for total nitrogen (TN) and Mehlich-3 P (M3P) using the methods noted in Table 3.2. Phosphorus results were converted by the lab to PFIV values. Additional soil analyses were discussed previously in Chapter 4. Turfgrass coverage was quantified using the methods described in Chapter 3.2.4.

5.2.3 Greenhouse Study

The greenhouse microcosm study was conducted at UMD's Greenhouse Complex in College Park, MD. Microcosms were constructed from 51 × 74 cm plastic tubs (4 replicates per treatment) that permitted collection of subsurface leachates. Microcosm design details were previously described in Chapter 4. To briefly recap, the topsoil used in the GHS came from Pleasants Construction, Inc (Clarksburg, MD). It was originally sourced from a forested area that was cleared for development and was stored in an exposed stockpile for at least one year before use in the GHS. Tubs receiving the C and F treatments were filled with soil to a depth of 10.16 cm. Tubs receiving NB, NBWF, and OBWF were filled to a depth of 12.7 cm, which included 10.16 of soil and 2.54 cm of amendment. Note that these were the same soil and amendment ratios which were used in the field study. Microcosms were randomized by treatment on three different benches in the greenhouse. Initial and final soil samples were collected and sent to Matrix Sciences for analysis as previously described.

The microcosms were seeded on Oct 5, 2022, with the same cool season turfgrass seed mix used in the field study. Seeds were distributed at the same rate, 224 $kg{\cdot}ha^{-1}$. At the end of the nine-week study, the heights of 10 randomly selected primary shoots per tub were measured with a ruler from the base of the crown to the tip of the shoot. Then, the entire shoot mass of each microcosm was cut 1 cm above the soil surface. These shoots were placed in paper bags and dried at 50°C. After 72 hrs, shoot dry mass were recorded and were shipped to Matrix Sciences for analysis of tissue contents as described in the previous section.

Biweekly simulated rain events (SREs) equivalent to a 25.4 mm rainstorm event (8,720 mL per microcosm) were applied to each tub at an approximate rate of 101.6 $mm \cdot hr^{-1}$ (4 $in \cdot hr^{-1}$). After applying treatments and before seeding, microcosms received one SRE. Four additional SRE's were applied after seeding. Supplemental water was applied as needed to aid germination and growth between SREs. However, only enough water to wet the soil surface was applied and not enough to produce leachate. Leachate analysis results were discussed in detail in Chapter 4. Here, cumulative TN and TP mass leachate losses are discussed in conjunction with post-experiment TN and PFIV results, N and P plant uptake results, and growth measurement results to draw conclusions about nutrient use efficiencies.

5.2.4 Statistical Analyses

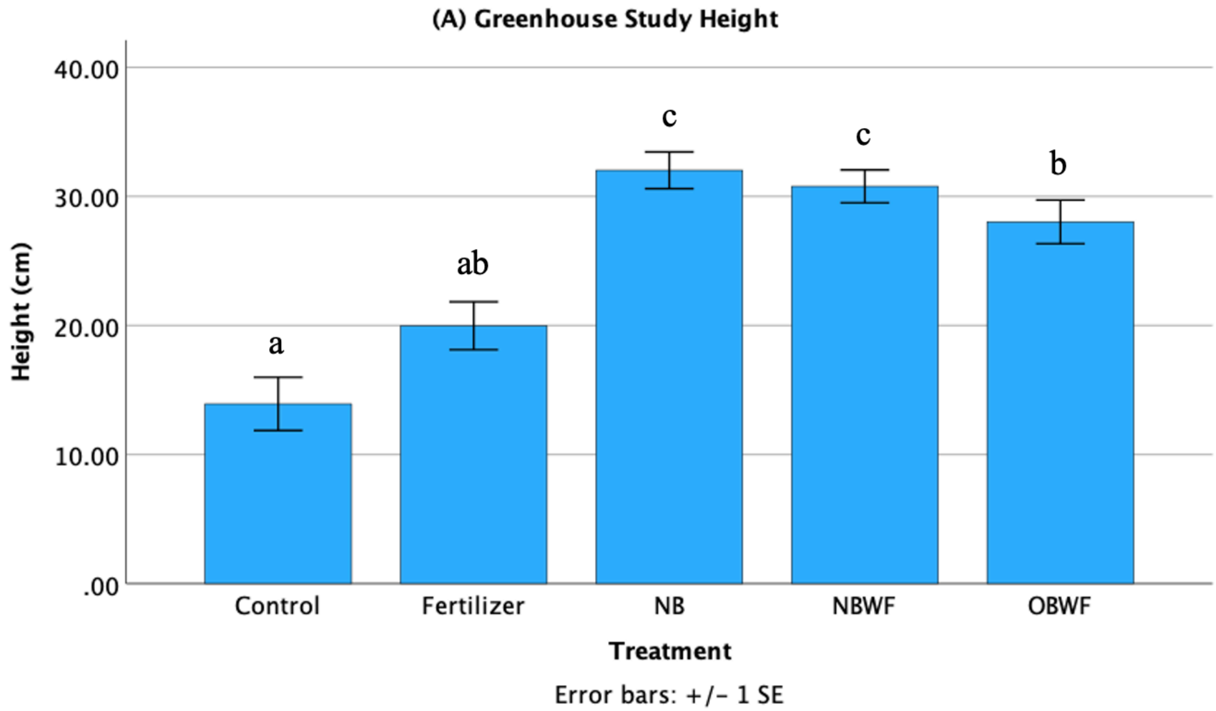
Results were analyzed using IBM SPSS version 29 (IBM Corp., Armonk, NY). Homogeneity of variance was determined by using Lavene's test. Where indicated, a one-way analysis of variance (ANOVA) was performed to compare treatment effects between soil nutrient concentrations, growth measurements, leachate losses and tissue nutrient concentrations. When ANOVA revealed that there was a statistically significant difference between at least two groups ($\alpha = 0.05$), a post-hoc test was performed using either the Bonferroni Correction or the Games-Howell test, for instances where variance was unequal. Lastly, pairwise t-tests were performed on select before/after soil measurements to determine if nutrient concentrations were statistically different. When statistical differences are mentioned, treatment means, standard errors (SE), *t*-values, *p*-values, and partial eta squared (where applicable) are listed within the text or the specified table/figure.

5.3 Results

5.3.1 Greenhouse Study

Mean shoot heights and shoot dry masses were statistically different between GHS treatments ($p < 0.001$). Means and pairwise comparisons are summarized in Figure 5.4.A-B. Height for the C treatment (13.9 cm ± 3.6) was low compared to the NB (32.0 cm ± 2.9) and NBWF treatments (30.8 cm ± 2.2). Height for the OBWF treatment (28.0 cm ± 2.9) was not different than the F treatment (19.1 cm ± 3.2) even though height differences between the OBWF and NBWF/NB treatments were smaller. This result was unexpected given the amount of plant available nitrogen in the OBWF treatment when it was applied (Table 5.1). Pairwise comparisons for shoot dry mass followed the same pattern as for plant height, and ranged from 6.4 g ± 2.1 for the C to 34.8 g ± 8.7 for the NBWF treatment. Again, the means for the F (14.6 g ± 6.6) and OBWF (25.1 g ± 3.7) treatments were similar.

Statistical similarities between OBWF and F treatment means have two explanations. First, avoidance of mean differences can be explained by the Bonferroni Correction. Lower risk of Type I errors and higher risk of Type II errors are a known trade-off when applying the post hoc method to multiple pairwise comparisons (Armstrong, 2014). A second explanation, likely working in conjunction with the first, involves early/heavy N losses through leaching. The microcosms experienced leaching one time prior to seeding with the first 25.4 mm SRE, to assess “worse case” pre-establishment losses. Microcosms experienced another leaching event two weeks after seeding with a second SRE, just after sprouts emerged, followed by 3 more bi-weekly SREs. The results from Chapter 4 showed that the majority of N was lost during the first two SREs (equivalent to 50.8 mm of rainfall) and N speciation was dominated by nitrate/nitrite (NOx). By SRE3, the F and OBWF NOx mass losses were similar, indicating that the amount of nitrate available for uptake was comparable for the two treatments (Chapter 4, Figure 4.14). On the other hand, NB and NBWF maintained high NOx losses for the entire 10-week experiment, demonstrating prolonged access to plant available nitrogen (PAN) throughout the establishment phase.



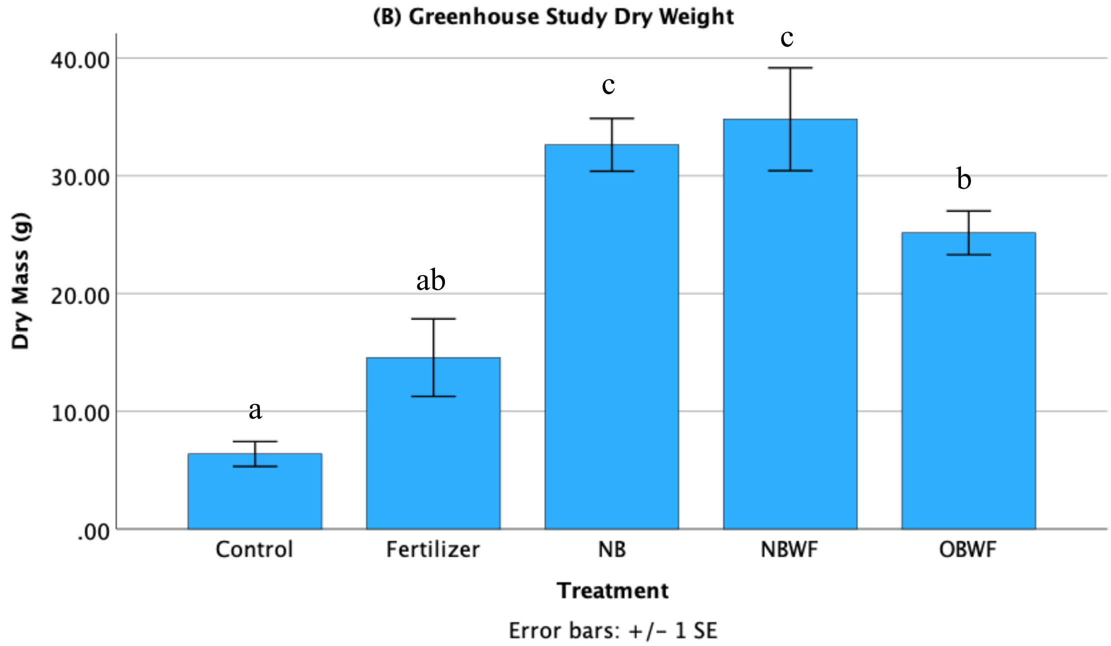


Figure 5.4. Height (A) and shoot dry mass (B) results for the Greenhouse Microcosm Study. Treatments included an unamended control soil, soil treated with a fertilizer, and soil amended with either fresh biosolids (NB), NB and wood fines (NBWF) or old biosolids and wood fines (OBWF). The Bonferroni correction was used for post hoc comparisons. Bars annotated with different letters are significantly different.

The analysis of GHS shoot dry mass helps to confirm that PAN was limited in the C, F, and OBWF treatments (Table 5.2). Even though the mean concentration of N was greater in OBWF clippings than C and F clippings, it was below the average sufficiency range for *Festuca arundinacia* (Mills and Jones, 1996). Results from the tissue analysis support that the NB and NBWF treatments provided sufficient access to PAN despite heavy leaching. Finally, the tissue analysis results show that grass accumulated sufficient concentrations of P in the NB, NBWF and OBWF treatments without soil releasing heavy loads into leachate, which will be discussed later.

Table 5.2: Summary of shoot tissue nutrient concentrations for the Greenhouse Study. Results which fall below sufficiency ranges for *Festuca arundinacia* (Mills and Jones, 1996) are annotated with boldface type. Results are expressed as mean ± the SE. ANOVA was performed to determine if significant differences existed between treatments. Values in columns which have different letters are significantly different (α = 0.05). Post hoc pairwise comparisons were made using the Bonferroni Correction.

	%N	**%P**
Sufficiency Range	***3.4 – 4.65***	***0.27 - 0.37***
C	**1.94 ± 0.06a**	**0.25 ± 0.01a**
F	**2.4 5 ± 0.13a**	0.28 ± 0.02a
NB	5.69 ± 0.05c	0.5 ± 0.02c
NBWF	5.24 ± 0.18c	0.32 ± 0.02ab
OBWF	**3.29 ± 0.12b**	0.40 ± 0.03b
ANOVA Result	$p < 0.001$	$p < 0.001$

<u>*5.3.2 Field Study*</u>

The "worst-case" rain scenario actually occurred at the beginning of the field study. Four days after seeding, the remnants of a tropical storm precipitated 51.1 mm of rainfall continuously over four days. Shoot height measurements were taken seven weeks after seeding and prior to the first mow. Results ranged from 8.0 ± 1.2 cm for the C treatment to 15.3 ± 1.2 cm for the NB treatment (Figure 5.5.A). Here too, the mean height for the OBWF treatment (8.7 ± 0.9 cm) was not significantly different from the mean height of the C and F (10.0 ± 0.8 cm) treatments ($p < 0.001$). Based on the GHS results, a large loss of nitrate via leaching from the OBWF plots near the time of seeding could explain why OBWF growth responses were similar to C responses, despite the high rate of PAN that was applied to OBWF plots.

Plots were not fertilized in the spring, to assess the residual effects of the treatments on growth during the second growing season. By this time, plots were fully established, but differences in height and shoot dry mass persisted through late April ($p < 0.001$; and $p < 0.001$, respectively). Although shoot growth measurements were higher for the OBWF treatment by this time, they remained comparable to the C and F treatments, while results for the NBWF and NB treatments were again greater (Figure 5.5.A-B). However, by late May, only the NB had significantly greater height than the other treatments ($p = 0.028$). Interestingly, the shoot dry mass for the OBWF treatment by May was greater than for all other treatments ($p < 0.001$).

Cumulative (Sept 2022 – June 2023) mean height and shoot dry mass results highlight the persistence of the treatments effects on growth. Height and shoot dry mass measurements for NB and NBWF were higher than the measurements for the control for the duration of the study. However, results show that increased height in the fall for the F treatment (as compared to the control) was only temporary and did not persist throughout the course of the study (Table 5.3).

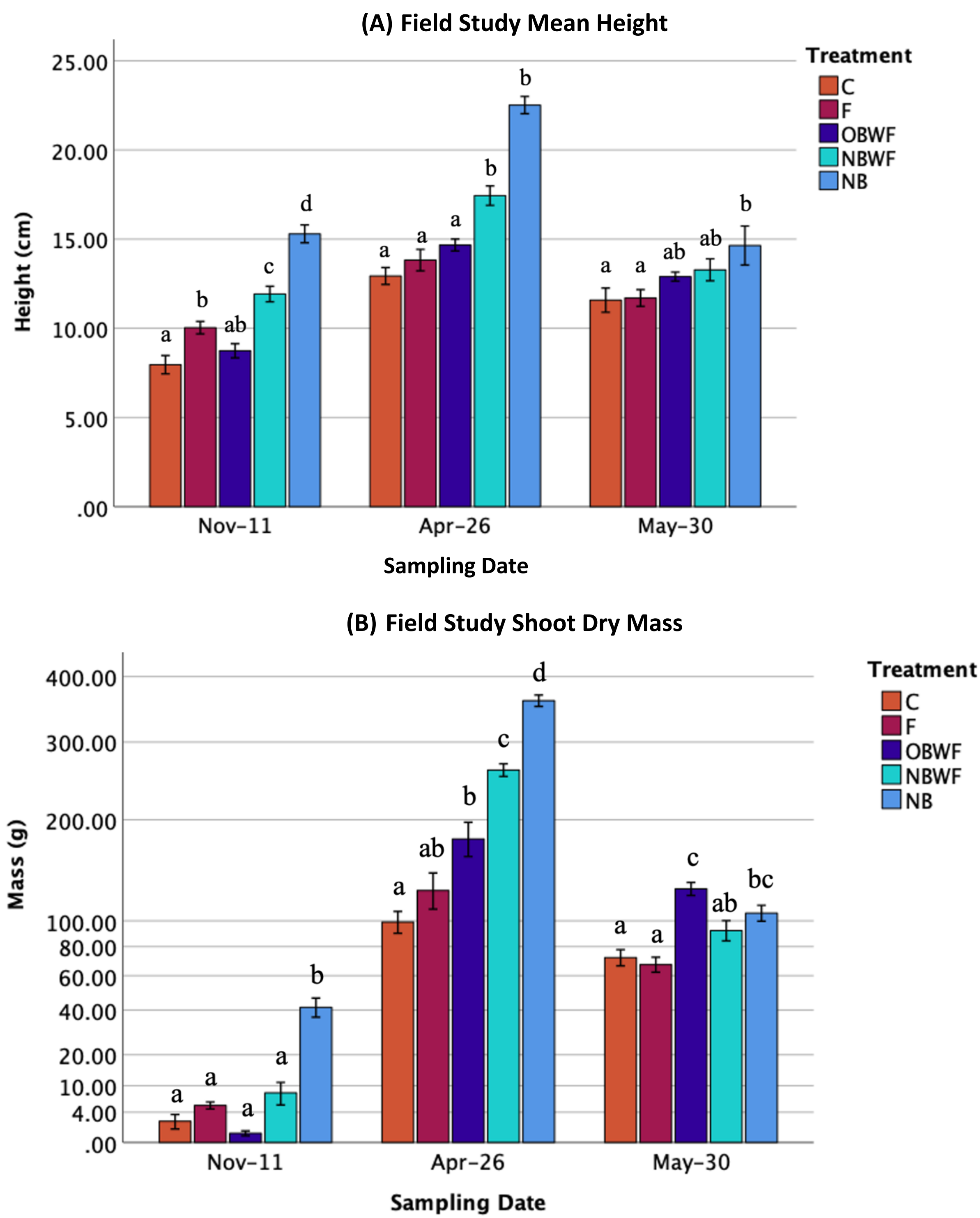


Figure 5.5. Spring and fall height (A) and shoot dry mass (B) assessments for the Field Study. Treatments included an unamended control soil (C), soil treated with a fertilizer, and soil amended with either fresh biosolids (NB), NB and wood fines (NBWF) or old biosolids and wood fines (OBWF). Error bars represent ±1 SE. Values with the same date but different letters are significantly different ($\alpha = 0.05$). Post hoc pairwise comparisons were made using the Bonferroni Correction.

Table 5.3: Field Study cumulative height and shoot dry mass results. Results are expressed as mean ± the SE. ANOVA was performed to determine if significant differences existed between treatments ($\alpha = 0.05$). Values in columns which have different letters are significantly different, as determined by Bonferroni post-hoc pairwise comparisons.

Treatment	Height (cm)	Shoot Dry Mass (g)
C	51 ± 1.8a	427 ± 31a
F	56 ± 1.9ab	508 ± 54a
OBWF	59 ± 1.7b	706 ± 50b
NBWF	74 ± 1.6c	1041 ± 35c
NB	98 ± 2d	1576 ± 39d
ANOVA result	$p < 0.001$	$p < 0.001$

The fall height and dry mass differences were somewhat reflected in the turfgrass coverage results, in that coverage was highest for the plots that received the NB treatment (Figure 5.6). However, the presence of weeds in the C and F treatments skewed the results of the digital analysis, which measured coverage based on the number of green pixels, regardless of their source. Thus, the digital analysis represents overall vegetative coverage, not just turfgrass coverage.

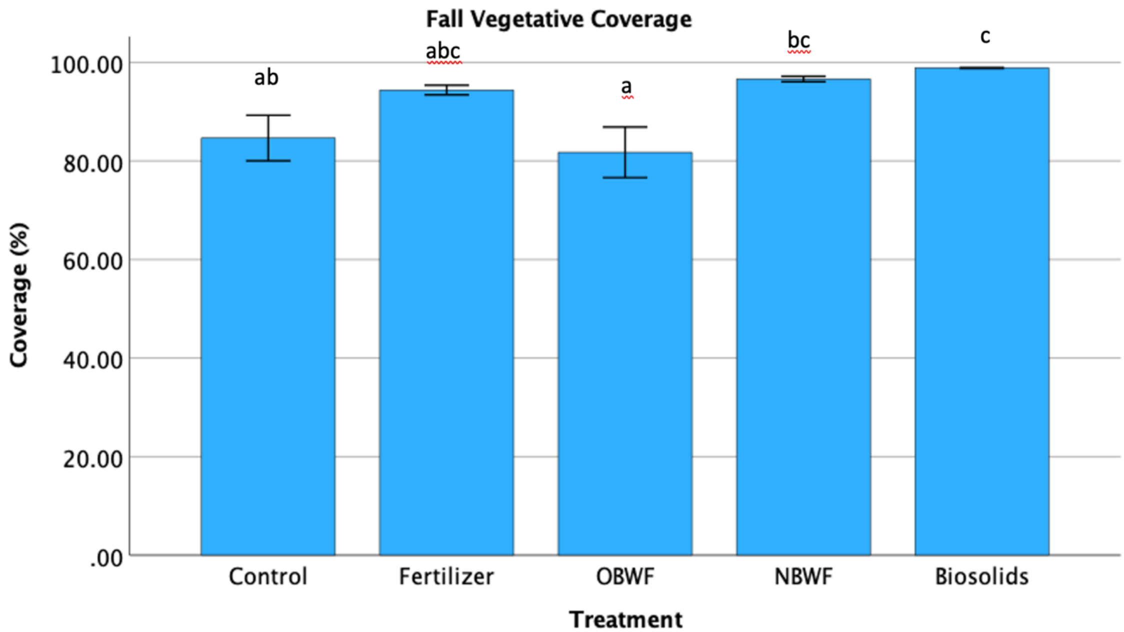


Figure 5.6. Field Study vegetative coverage seven weeks after seeding (November, 11 2022). Treatments included an unamended control soil (C), soil treated with a fertilizer (F), and soil amended with either fresh biosolids (NB), NB and wood fines (NBWF) or old biosolids and wood fines (OBWF). Error bars represent ±1 SE. Bars annotated with different letters are significantly different ($\alpha = 0.05$). Post-hoc pairwise comparisons were made using the Bonferroni Correction.

As the plot pictures show in Figure 5.7, the C and F treatments had more weed growth than the other treatments. The OBWF, NBWF and NB amendments were tilled into respective research plots, which likely disrupted weed germination (noted from personal observation). The tiller was tested on a disturbed area adjacent to the research plots. Weeds were completely absent from the test area but copious in the surrounding area up to the line of demarcation seven weeks after tilling, when the pictures were taken for the digital analysis. This observation suggests that *re-disturbing* disturbed soil just prior to seeding suppressed weeds in the OBWF, NBWF and NB plots as well. By the middle of the second growing season, coverage was 100% for each treatment (Figure 5.8). Plots treated with OBWF, NBWF, and NB remained weed-free.

However, weeds were still present in the C and F plots despite the application of an herbicide in the fall.

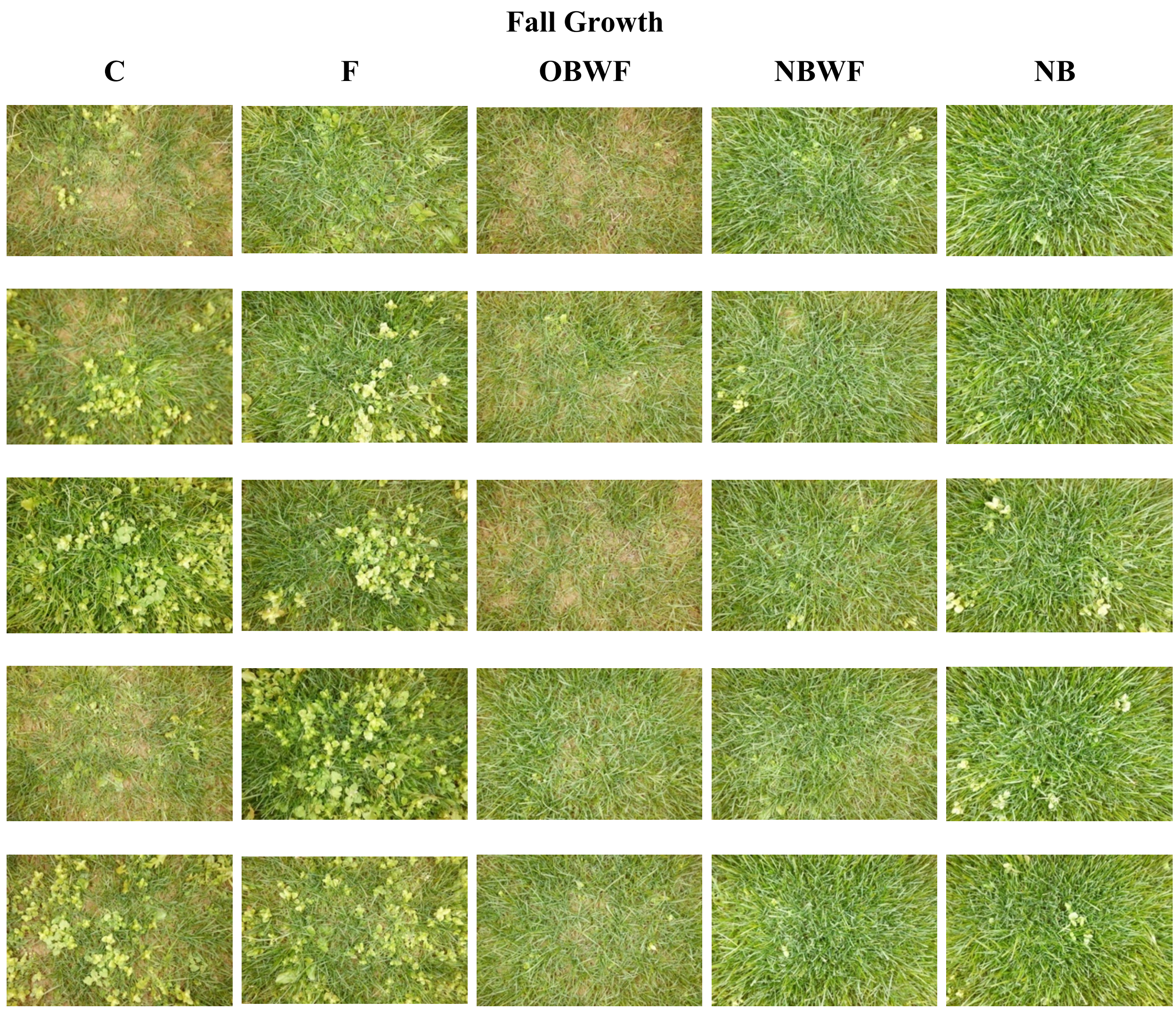


Figure 5.7. Field Study growth progress seven weeks after seeding. Treatments included an unamended control soil (C), soil treated with a fertilizer (F), and soil amended with either fresh biosolids (NB), NB and wood fines (NBWF) or old biosolids and wood fines (OBWF).

While erosion losses are typically inversely related to coverage (Snelder and Bryan, 1995), the uniformity of coverage is an important factor. Clumpy vegetation can lead to flow concentration between plants, resulting in increased runoff velocity and higher sediment losses (Morgan, 2007). Furthermore, uniformity is a factor that determines turfgrass quality, which is a measure of aesthetics more so than yield by most standards (Morris and Shearman, 1998).

Hence, incorporating amendments into soil provided an unanticipated potential benefit. Additional studies were not identified which addressed this observed phenomenon directly. Therefore, it would provide an interesting topic for future research.

Spring Growth

C	F	OBWF	NBWF	NB

Figure 5.8. Field Study plots on May 5, 2023, seven months after seeding. Treatments included an unamended control soil (C), soil treated with a fertilizer (F), and soil amended with either fresh biosolids (NB), NB and wood fines (NBWF) or old biosolids and wood fines (OBWF).

As discussed in Chapters 3 and 4, soil test results show overall improvements to nearly all macro- and micro-nutrients after biosolids were incorporated into FS plots, even after two growing seasons (Appendix F). Long term increases included: PAN, M3P, Fe, Ca, S, B, Zn, and

Cu (NBWF and NB). However, decreases in Mn and K (NBWF and NB) were noted. As opposed to the GHS control soil, which had an "optimum" PFIV value (78) meaning that a yield response was unlikely, the FS control soil PFIV (27) was borderline "low". This indicates that a yield response to P fertilization was *likely*. All treatments improved soil M3P at the beginning of the experiment, but biosolids amendments had a greater effect than fertilizer (Table 5.4). By the end of the experiment, the PFIV values for the C, F and NBWF treatments, were significantly lower than starting values. Maintenance P fertilizer applications would be allowed on the C and F plots under current UMD fertilizer recommendations. However, PFIV values remained optimum for OBWF, NBWF and NB, which means that maintenance P would not be allowed.

Table 5.4: Field study initial and final phosphorus field index values (PFIV) and Mehlich-3 P (M3P) test results. Results are expressed as mean ± SE. ANOVA was performed to determine if there were significant differences in treatment results within sampling sets. Letters within rows that are different indicated significant differences (α = 0.05). Same sample t-tests were performed on initial and final treatment results. Treatment columns that contain a p-value are significantly different (α = 0.05).

Measure	**C**	**F**	**OBWF**	**NBWF**	**NB**	**ANOVA *p*-value**†
$PFIV_I$	27 ± 3a	38 ± 4a	74 ± 13ab	70 ± 4b	105 ± 9b	$p < 0.001$
$PFIV_F$	15 ± 1a	16 ± 1a	65 ± 6bc	58 ± 1b	84 ± 4c	$p < 0.001$
t-test *p*-value*	0.025	0.009	-	0.26	-	
$M3P_I$	23.2 ± 63a	33.0 ± 4a	76.2 ± 4b	62.8 ± 3b	94.8 ± 8b	$p < 0.001$
$M3P_F$	12 ± 1a	13 ± 1a	57 ± 5bc	51 ± 1b	75 ± 3c	$p < 0.001$
t-test *p* value*	0.23	0.11	0.25	0.25	-	

* A *p*-value is listed in cases where initial and final results are significantly different.
† The Bonferroni Correction was used in the post hoc analysis of the PFIV results; and the Games Howell post hoc test was used for the analysis of the M3P results.

Even though higher concentrations of P in soil amended with biosolids likely contributed to increased yields, the influence of N is generally accepted as a much more important factor in determining establishment and growth, especially because N availability has been tied to P activity in the rhizosphere (Koper and Lemanowicz, 2008; Paredes et al., 2011). Therefore, differences in N application rates largely explain differences in cumulative height and shoot dry mass such that NB > NBWF > OBWF > F = C.

Quarterly soil analyses showed that treatments increased plant available nitrogen (ammonium and nitrate, PAN). However, concentrations generally decreased in subsequent quarters (Figure 5.9). Soil PAN losses are explained by leaching, volatilization, denitrification, and plant uptake. Since clippings were removed for experimental purposes, PAN (as well as other plant nutrients) was likely lower across all treatments than it would have been if clippings were allowed to decompose in place (Starr and DeRoo, 1981; Law et al., 2017; Benjamin et al., 2017). This likely diminished treatment effects to some degree. Despite the general PAN losses, there was a slight mean increase in March 2023 noted in the OBWF soil test result. However, it was not enough to explain the increase in OBWF shoot dry mass that occurred towards the end of the second growing season. By that point in the experiment, the concentration of PAN was similar to the F and C mean concentration.

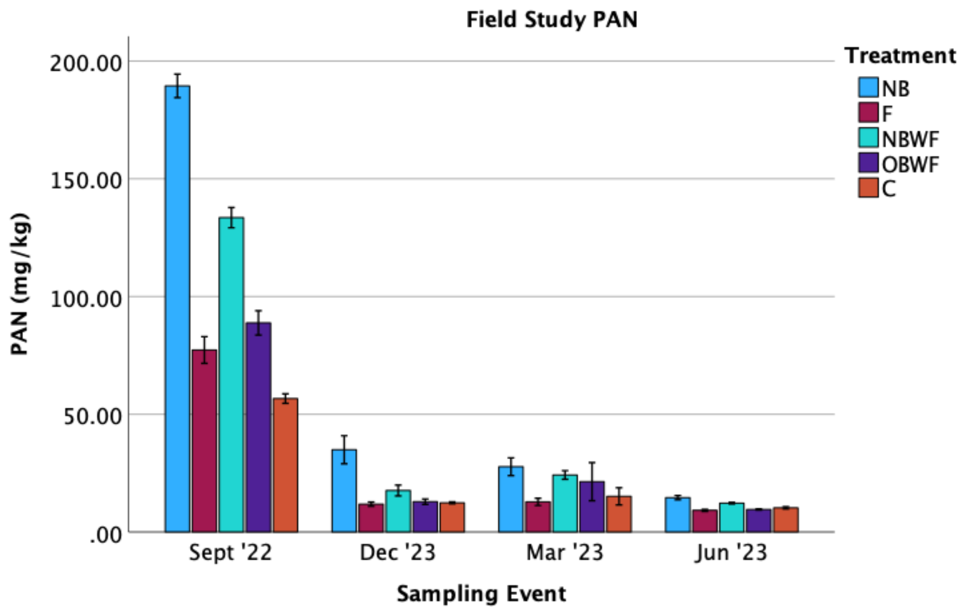


Figure 5.9. Mean plant available nitrogen (ammonium and nitrate - PAN) by treatment and quarter. Treatments included an unamended control soil (C), soil treated with a fertilizer (F), and soil amended with either fresh biosolids (NB), NB and wood fines (NBWF) or old biosolids and wood fines (OBWF). Error bars represent ±1 SE.

A review of soil sensor data results (including temperature and VWC – discussed later), tissue analysis results (including the macro- and micronutrients) and soil test results (including OM, cation exchange capacity, M3P, nitrate, ammonium, macro- and micronutrients), did not offer a clear explanation for increased OBWF shoot dry mass results (as compared to other treatments) towards the end of the experiment, with one exception – soil pH (Figure 5.10). In March, the mean pH for the OBWF treatment was 6.16. The pH for the other treatments ranged from 5.60 – 6.00. In June, the pH for OBWF was still higher at 5.96, with treatments ranging from 5.64 – 5.85. Even though, post hoc analyses revealed that OBWF pH means for March and June were only significantly greater than respective NB means, the pH scale is logarithmic. Therefore, small changes in pH between 5.50 and 6.50 can represent significant differences in H^+ activity. Furthermore, it is generally accepted that nutrient availability is most favorable between

6.0 and 7.0 in mineral soils. The classic view regarding P availability is that maximum P solubility peaks twice - around 4.5 and again at 6.5 (Penn and Camberato, 2019).

The availability of P in the FS soil would have been an important factor since the PFIV value of the control soil indicated that yield responses were likely to occur if P was applied. Therefore, greater P solubility tied to a more favorable pH explains why OBWF dry mass measurements were higher than the other treatments towards the end of the experiment. The second season OBWF growth responses are important to mention because they highlight the complexity of factors that contribute to growth and performance.

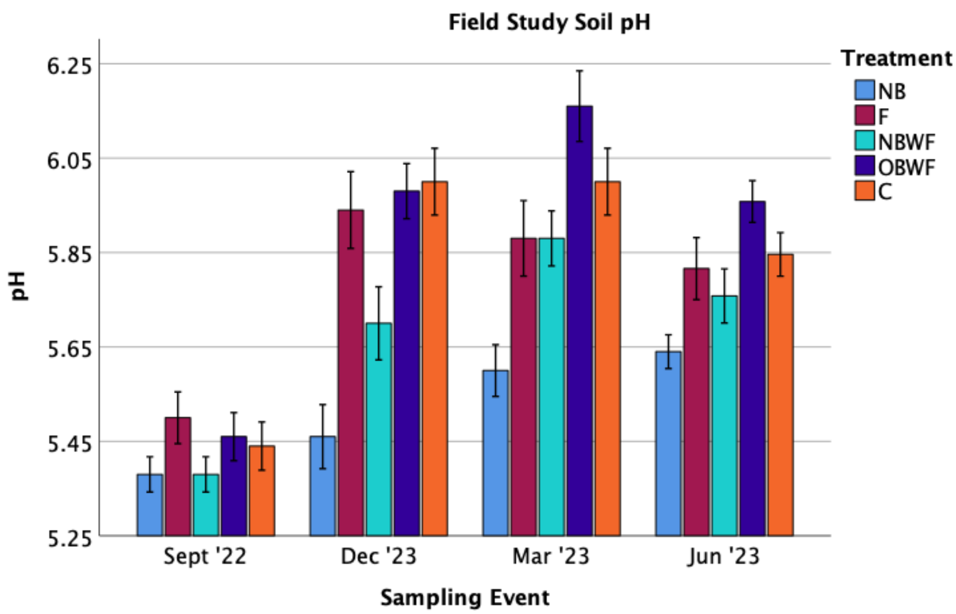


Figure 5.10. Mean soil pH by treatment and quarter. Treatments included an unamended control soil (C), soil treated with a fertilizer (F), and soil amended with either fresh biosolids (NB), NB and wood fines (NBWF) or old biosolids and wood fines (OBWF). Error bars represent ±1 SE.

Overall spring growth enhancements may be better explained by differences in the concentration of soil organic matter (OM) since OM is tied to numerous chemical and physical metrics that enhance soil health, including: nutrients, cation exchange capacity, bulk density, porosity and aeration (Diacono and Montemurro, 2010; Dunifon et al., 2013; Schmid et al., 2017; Ferreiro et al., 2020). Throughout the experiment the concentration of OM was significantly higher in soil treated with NB, NBWF, and OBWF ($p < 0.001$) (Table 5.5).

Table 5.5: The concentration of organic matter (OM) in amendments (Chapter 4) and the mean soil OM concentration after eight months. Results are expressed as mean ± SE. ANOVA was performed to determine if significant differences existed between treatments ($\alpha = 0.05$). Values in columns which have different letters are significantly different, as determined using the Bonferroni Correction for the post hoc analysis.

Treatment	Amendment OM Concentration (%)	Average Soil OM Concentration (%)
C	-	3.38 ± 0.07a
F	-	3.40 ± 0.08a
OBWF	20.03	4.08± 0.06b
NBWF	24.37	3.98 ± 0.09b
NB	18.03	4.5 ± 0.09c

A long-term turf establishment study conducted along a highway embankment provided evidence of a yet another soil benefit related to OM that could be relevant in this study in which irrigation was not provided after the first week. Fava (2016) showed that plots with higher OM concentrations performed better two years after seeding. The researcher tied performance improvements to increased soil moisture and concluded that higher OM additions to plots provided long-term benefits beyond immediate fertilization. Werner et al. (2020) later showed that losses in soil OM under sustained high temperatures decreased water holding capacity, which thereby decreased thermal buffering. What resulted was a self-reinforcing feedback loop. Xu and Huang (2000) showed that high soil temperatures lowered grass quality. With these studies in mind, the effects of the treatments on the daily minimum soil VWC and maximum daily soil temperature were examined for one week near the end of May. The week selected coincided with the highest post-establishment air temperatures (Appendix G). The results did not provide strong evidence either for or against previous research findings as discussed below.

Daily minimum VWC treatment averages are summarized in Figure 5.11. Averages in May for the NBWF treatment were higher than C and F treatment averages. These results support the research findings described by Fava (2016), who showed that increases in OM from compost increased soil moisture, because the C and F treatments had lower OM concentrations. However, daily VWC averages for the NB treatment were comparable to C and F treatment averages even though NB had the highest concentration of OM. Additionally, daily VWC averages for the OBWF treatment were lower than the averages for the C and F treatments even though OBWF had a higher mean concentration of soil OM than C and F treatments.

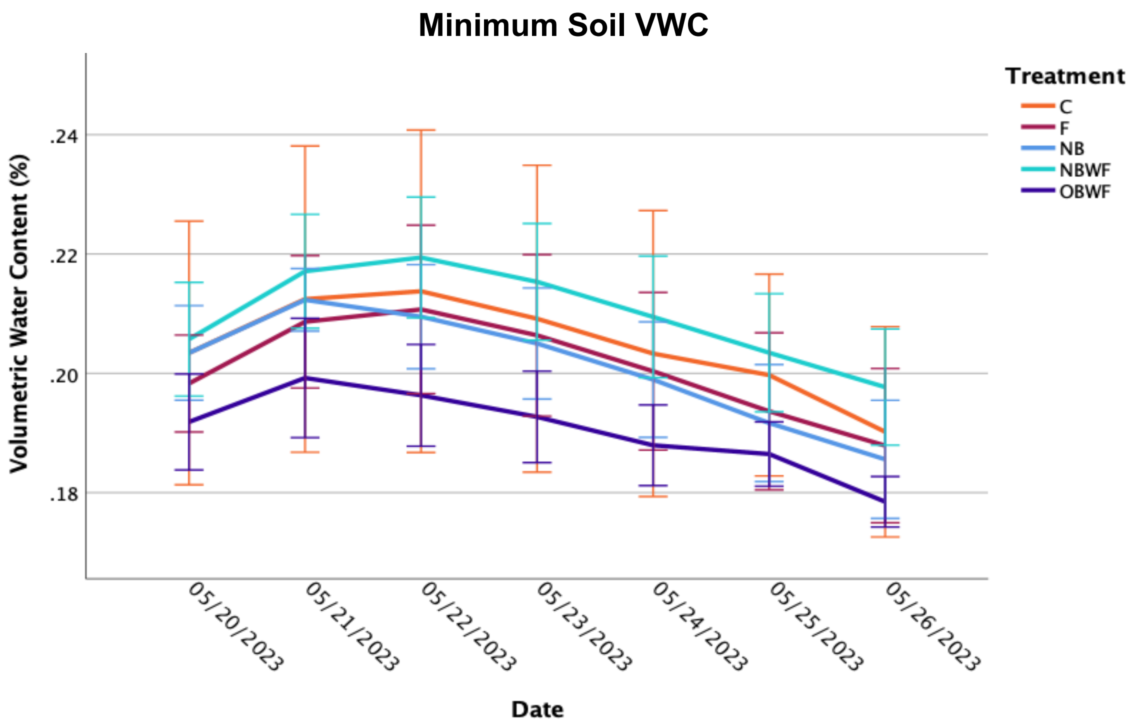


Figure 5.11. Average daily minimum soil volumetric water content by treatment for May 20, 2023 to May 26, 2023. Treatments included an unamended control soil (C), soil treated with a fertilizer (F), and soil amended with either fresh biosolids (NB), NB and wood fines (NBWF) or old biosolids and wood fines (OBWF). Error bars represent SD.

Maximum daily soil temperatures were lowest for the NB and NBWF treatments and highest for the C treatment (Figure 5.12). These results indicate that there was a treatment effect on soil temperature related to biosolids addition. However, soil temperature differences are not explained clearly by treatment effects on VWC, as Werner et al. (2020) demonstrated. This is because the daily NB VWC average was lower than or equal to the daily average for the C treatment, which indicates that they should have had similar daily temperatures. However, they were on opposite sides of the spectrum for daily maximum temperature. Additionally, C plots had the highest daily temperature even though OBWF plots had the lowest VWC. Therefore, another factor, perhaps canopy density, may have been at play to lower soil temperature and/or soil moisture via transpiration. However, these are mere speculations since canopy density and transpiration were not measured.

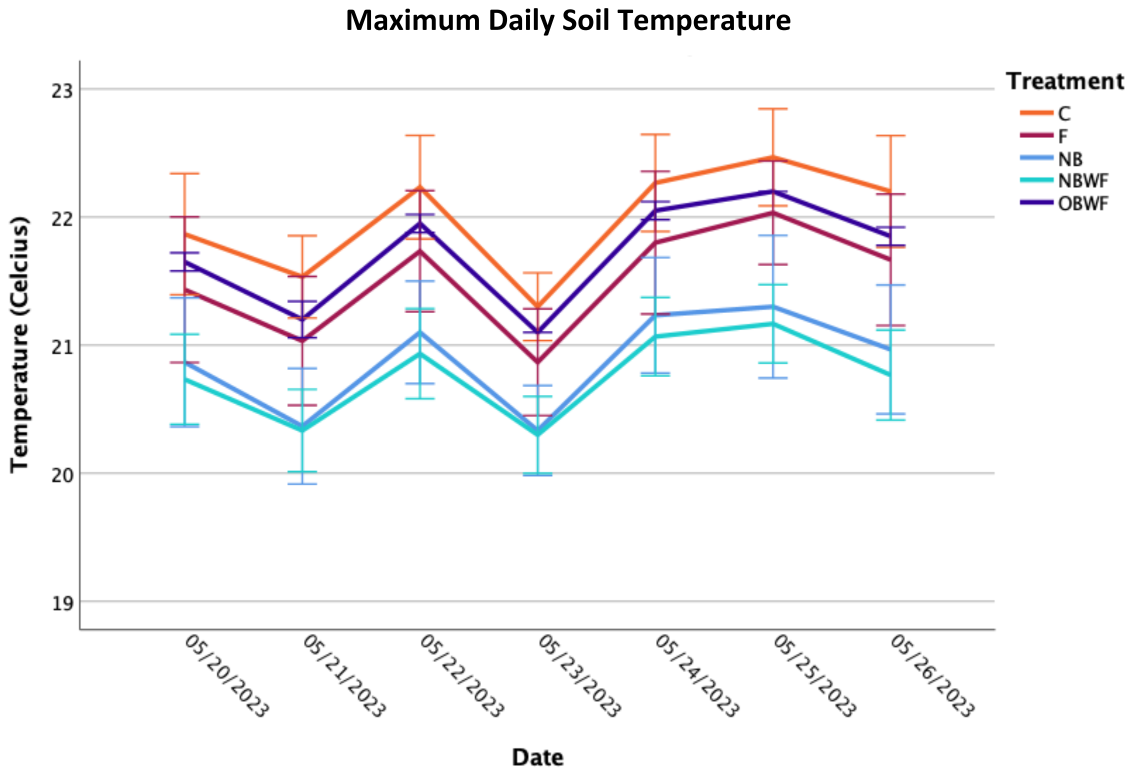


Figure 5.12. Average daily maximum soil temperature by treatment for May 20, 2023 to May 26, 2023. Treatments included an unamended control soil (C), soil treated with a fertilizer (F), and soil amended with either fresh biosolids (NB), NB and wood fines (NBWF) or old biosolids and wood fines (OBWF).

Overall, results from this study do not strongly reject the research findings described by Fava (2016) since they were conducted over a limited timeframe and with a limited number of replicates (n = 3). Nevertheless, findings warrant further research on how biosolid and wood fine co-amendments affect VWC, since VWC can affect soil temperature and ultimately growth as shown by Fava (2016) and Xu and Huang (2000). Evidence of a strong positive relationship between biosolids, VWC, and growth could help to justify high application rates, especially in low maintenance environments, since healthy vegetative covers are widely promoted as a stormwater best management practice for reducing erosion.

5.3.3 Greenhouse Microcosm Nutrient Recovery and Loss Summary

Pairwise comparisons of the initial and final PFIV results for the C and F treatments were not significantly different (data not shown, $p = 0.1$ and $p = 1.0$, respectively). However, PFIV increased by 22%, 36%, and 44% for OBWF, NBWF and NB, respectively over the course of the study. Final values are listed in Table 5.6. Despite these large increases in availability, P losses from soil amended with biosolids was minimal in comparison to losses from soil that received the F treatment (Table 5.6). Chapter 4 concluded that biosolid amended soil retained P due to increases in Fe and Ca. All microcosms, except those that received the F treatment, retained most of the P applied as well the P that was present in the tap water used to simulated rain (12.06 $mg \cdot L^{-1}$ total). Furthermore, the OBWF and NBWF treatments leached less P than the control. Yet, plant uptake was sufficient in all soils that received one of the biosolids treatments and far exceeded mass leachate losses. Although encouraging, this study is limited in its findings since a single soil with low P saturation was used. Loss from biosolid amendments could be higher from soils with higher initial P saturation. Additionally, this study only evaluated leachate losses. However, several studies, including this one as described in Chapter 4, note that P losses are primarily associated with particulate losses. Therefore, P losses associated with erosion could be high regardless of P saturation.

Nitrogen uptake was greater than N leaching losses for the C, F, and OBWF treatments. On the other hand, leaching losses were greater for the NBWF and NB treatments. The NBWF treatment leached 1.38 times more N than was taken up, with more losses expected given additional simulated rain events (Chapter 4). From a different perspective, NBWF treatments leached 9.5 times more N than the F treatments, which are losses that are controlled by current UMD turfgrass establishment recommendations. It should be noted that N losses for the F treatment were similar to C losses by the last simulated rain event. Therefore, additional losses were not expected given additional simulated rain events. The NB treatment leached 9 times more N than was taken up, and 62 times more N than the F treatment, which was a startling result. Had the experiment continued, additional losses could have been expected based on the high mean leachate mass losses from the last simulated rain event as well at the high mean concentration of TN present in the soil at the end of the experiment (70% higher than the C). Nitrogen uptake was not significantly different between the NBWF and NB treatments, and a review of the entire tissue analyses (data not shown) provide no evidence that other nutrient deficiencies restricted growth in any way, which could have limited N uptake. Therefore, the additional N applied (43.51 g) to NB microcosms was excess N, which would be prone to release into the environment if this experiment was conducted in the field.

Table 5.6: Summary of microcosm phosphorus (P) and nitrogen (N) movement. Treatments included an unamended control soil (C), soil treated with a fertilizer (F), and soil amended with either fresh biosolids (NB), NB and wood fines (NBWF) or old biosolids and wood fines (OBWF). Results are expressed as mean ± SE. Where indicated with the inclusion of a p-value ($\alpha = 0.05$), ANOVA was performed to determine if significant differences existed between treatments. Values in rows which have different letters are significantly different.

	P Applied (mg)	**P Uptake (mg)**	**P Leached (mg)**	**Final Soil PFIV**
C	NA	16.1 ± 2.8a	12.3 ± 1.2a	84 ± 1.5a
F	590	42.4 ± 11.1ab	33.3 ± 4.1b	112 ± 3.6b
OBWF	24,495	99.9 ± 12.0bc	7.8 ± 1.3a	198 ± 6.3c
NBWF	16,785	106.7 ± 5.9c	6.9 ± 0.4a	252 ± 2.7d
NB	57,530	163.3 ±14.0c	15.1 ± 2.5ab	305 ± 5.5e
ANOVA Result		$p < 0.001$	$p < 0.001$	$p < 0.001$*
	N Applied (g)	**N Uptake (g)**	**N Leached (g)**	**Final Soil TN ppm**
C	NA	0.1 ± 0.02a	0.1 ± 0.01a	726 ± 15a
F	1.66	0.4 ± 0.08ab	0.3 ± 0.03b	863 ± 36a
OBWF	42.34	0.8 ± 0.08b	0.4 ± 0.03b	1417 ± 119b
NBWF	45.09	1.8 ± 0.16c	2.6 ± 0.7ab	1858 ± 50b
NB	88.6	1.9 ± 0.12c	16.8 ± 1.6c	2383 ± 33c
ANOVA Result		$p < 0.001$*	$p < 0.001$	$p < 0.001$*

* Post hoc pairwise comparisons were made using the Bonferroni correction. Others used the Games-Howell post hoc test.

5.4 Conclusions

With regards to turfgrass establishment, this study showed that UMD's current recommendation for incorporated organic amendments (2.54 cm) is excessive, if *pure* fresh biosolids are applied. At the current recommendation rate, growth for the NB treatment was overly productive compared to other biosolids treatments, which had lower N values but maintained reasonable growth rates and coverage. The cumulative height result for the NB treatment was 24% greater than the result for the NBWF treatment. In practical terms, this means that maintenance demands/costs on areas where 2.54 cm of fresh biosolids are applied will be higher – at least for the first year. While rapid establishment is important, the field study showed that percent coverage for NB and NBWF was comparable seven weeks after establishment. Both achieved near 100% coverage but nearly half as much N and P was applied to NBWF plots. By the following growing season, growth measurements for the three biosolids treatments were better than the control and fertilizer treatments. However, the differences between NB, NBWF and OBWF were smaller; and OBWF had a higher mean shoot dry mass than NB.

Nutrient recovery calculations demonstrated significant differences between the amount of N taken up by turfgrass and N leached. The cumulative mass leachate loss of N from the NB treatment was excessive when compared to accepted losses from the F treatment – nearly 62 times greater. While the average mass loss from the NBWF treatment was also greater, the magnitude of the difference was less – only 9.48 times greater than the F mass loss. However, growth improvements resulting from OM and TN additions may justify higher nitrate losses from NBWF treatments to prevent erosion losses associated with failed establishment. Additionally, there was some evidence that the NBWF treatment had positive effects on soil moisture and temperature. However, it was not clear why since the other biosolids treatments did not produce the expected results.

While P uptake was enhanced by the three biosolids additions, leachate losses were low. On the other hand, the F treatment leached 2 times more P but the tissue analysis indicated that there was a P deficiency in the F treatment clippings. Therefore, biosolids were a safer, more effective source of extractable P than the fertilizer. However, "excessive" post-study PFIV values indicate that soil treated with biosolids should be tested before additional P is applied. Current UMD recommendations address unnecessary P additions for turfgrass maintenance (not establishment) by requiring a soil test before using P fertilizers. Recommended maintenance rates depend on PFIV results. Manufactured soil that was blended with biosolids, likely does not need additional P for turfgrass establishment. However current recommendations do not prevent the use of P fertilizers on such soil.

Lastly, the results from Chapter 4 showed that N and P losses were universally highest, including from the manufactured control soil, for the first 2 -3 rain events. The Maryland Fertilizer Law addresses nutrient losses from bare soil with date restrictions that coincide with dormant periods (Nov 15 – March 1). Also, fertilizer applications are restricted before heavy rain, if the ground is frozen, and near water bodies. Similar restrictions for incorporated biosolids amendments could reduce leaching losses from disturbed soil.

5.5 Recommendations

UMD in conjunction with the Maryland Department of Agriculture should consider updating UMD Turfgrass Technical Update TT116 to include the following recommendations:

1. Incorporated biosolids applications should be limited to 1.27 cm of pure biosolid material.
2. Biosolids may be blended with a fine wood filler and used at a rate of 2.54 cm as long as the blend is incorporated into soil and biosolids do not exceed 50% of the blend.
3. Homeowners should not surface apply or incorporate biosolids between November 15 and March 1. Certified professional landscapers may incorporate or surface apply biosolids within the dates specified for synthetic fertilizers.
4. Biosolids should not be incorporated into soil within 15 feet of waterways, if heavy rain is predicted, or if the ground is frozen.
5. If manufactured soil was amended with biosolids offsite, a soil test should be conducted before applying additional fertilizer for turfgrass establishment. P shall be applied according to the recommendations specified for fertilizers when soil PFIV is known.

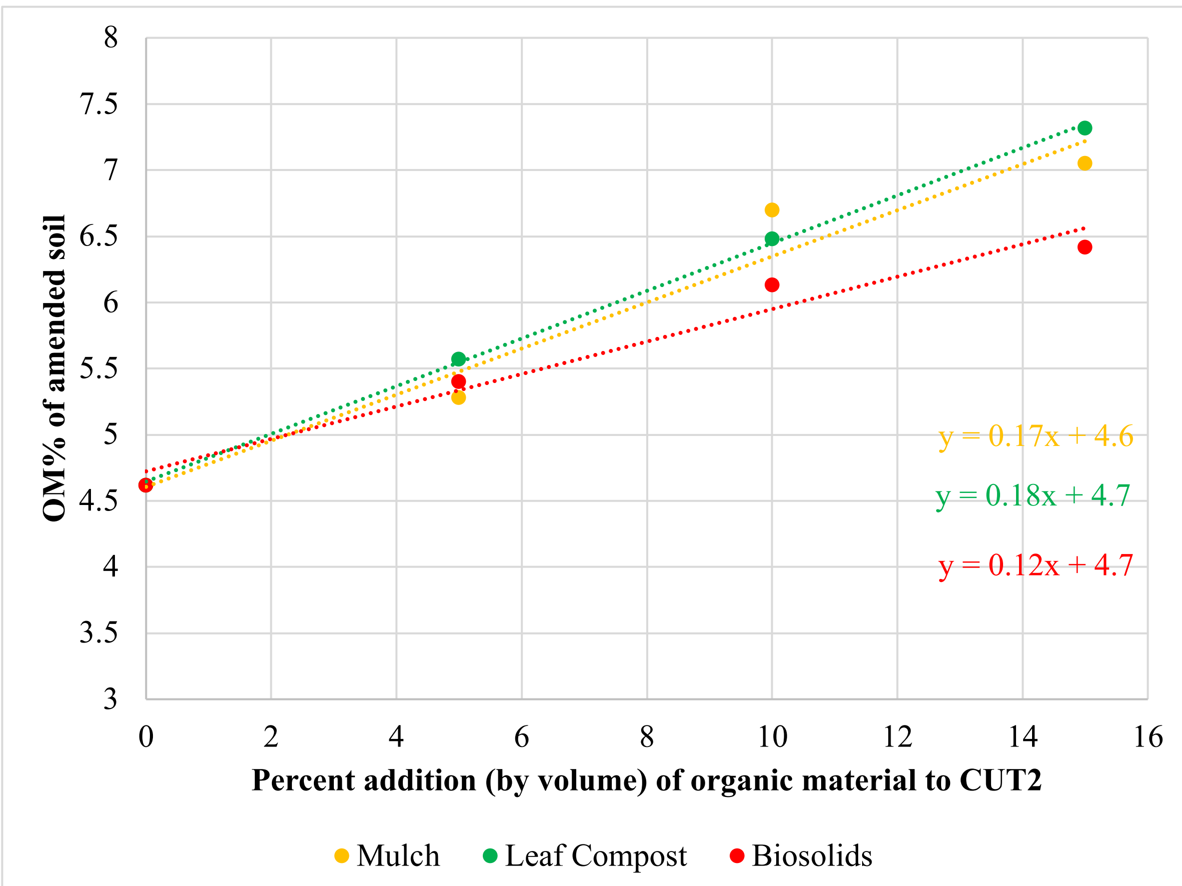
Appendix A

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?

Appendix B

This plot was used to determine the OM addition to the base soil (CUT2) for the Tub Study 2 treatments. The percent addition of organic material to the control soil (CUT2) was on a volume basis (x). The target concentration of OM in the amended soil (y) was 6%.



Appendix C

Soil analysis methods, instruments and lowest method detection limits (MDL) for the University of Maryland's Environmental Engineering Laboratory.

Soil Property	Units	Method	Instrument	Lowest MDL
pH	-	ASTM D4972	VWR symphony B40PCID	2
EC	μmho/cm	FAO method	VWR symphony B40PCID	0.001μmho/cm
OM content (LOI at 455 °C)	%	AASHTO T267	Thermonlyne^{TM} Muffle Furnaces	0.01%
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%
P, Al, Fe, Mg, Ca	mg/kg	Mehlich-3 extraction	Shimadzu Model ICPE-9820	1 mg/kg

Table S2. Chemical Properties of the Tub Study 1 and Tub Study 2 Soils

	Tub Study 1				Tub Study 2			
Measurement	CUT1	MAT1	LAT1	BAT1	CUT2	MAT2	LAT2	BAT2
OM (%)	7.2	6.32	6.03	5.76	4.34	6.86	5.92	5.64
EC (mmho/cm)	0.59	1.37	0.8	2.16	0.3	0.28	0.59	1.89
pH (1:1)	6.7	6.57	6.78	6.19	7.21	7.31	7.18	6.79
C (ppm)	31980	30215	29000	26662	15522	29631	25901	22868
N (ppm)	1242	1628	1958	3956	1386	1460	2223	2935
C:N ratio	25:1	19:1	15:1	7:1	11:1	20:1	12:1	8:1
NH_4-N (ppm)*	-	-	-	-	1.15	0.88	0.9	87.8
NO_3-N (ppm)*	-	-	-	-	35.1	28.3	81.2	137
P (ppm)	30	16	23	111	16	17	27	90
Ca (ppm)	1834	2171	1993	1311	2162	2412	2483	2681
Mg (ppm)	1503	126	378	181	143	153	206	196
Fe (ppm)	57	339	406	850	394	438	533	577
Al (ppm)	875	498	726	1023	786	832	984	861

**Analyses performed by Matrix Sciences, Chicago, IL (formerly AgroLab of Harrington, DE)*

Appendix D

The following series of calculations were used to determine nitrogen and phosphorus loading rates for the biosolids amendments used in the third greenhouse microcosm study and the field study.

Surface Area of microcosm (A_M)
Microcosms (mc)
10,000 m^2 = 1 ha

$$\frac{10{,}000\ m^2}{A_M} = \frac{mc}{ha}$$

Bulk density of amendment ($\rho_{amendment}$)
Volume of amendment per microcosm ($V_{a/mc}$)
Mass of amendment per microcosm ($m_{amendmenr/mc}$)

$$\rho_{amendment} \times V_{a/mc} = m_{amendment/mc}$$

$$\frac{mc}{ha} \times m_{amendment/mc} = m_{amendment/ha}$$

$$\%\ Nutrient\ in\ amendment \times m_{amendment/ha} = m_{nutrient/ha}$$

Example using the New Biosolids (NB) analysis results:

Surface Area of mc (A_M) = 0.51 m × 0.74 m = 0.3774 m^2
10,000 m^2 = 1 hectare

$$\frac{10{,}000\ m^2}{.3774\ m^2} = 26{,}497.09\frac{mc}{ha}$$

Bulk density of amendment ($\rho_{amendment}$)
Volume of amendment per microcosm ($V_{a/mc}$) = 0.51 m × 0.74 m × 0.0254 m = 0.00958596 m^3
Mass of amendment per microcosm ($m_{amendmenr/mc}$)
Concentration of nitrogen in amendment = 1.3%

$$673\frac{kg}{m^3} \times 0.00958596\ m^3 = 6.45135\ \frac{\mathrm{kg}}{mc}$$

$$26{,}497.09\frac{mc}{ha} \times 6.456135\frac{kg}{mc} = 171{,}068.79\frac{kg_{amendment}}{ha}$$

$$.0138 \times 171{,}068.79\frac{kg_{amendment}}{ha} = 2{,}361\frac{kg_{nitrogen}}{ha}$$

Appendix E

Maryland soil test fertility index value (FIV) ranges, category interpretations, and permissible phosphorus (P) application rates for turfgrass establishment (Carroll and Turner, 2016). Rates are based on the method of application. Incorporated products must be mixed into at least 5.08 cm of soil. Fertilizer rates do not apply to organic products, unless the products are surface applied.

FIV Value*	**Soil Test Category**	**Likelihood of Yield Response**	**Rate P_2O_5 kg•ha^{-1}**	
			Broadcast	**Incorporated**
0-25	Low	Yield response likely	98 - 146	146 - 195
26-50	Medium	Yield response possible	49 - 98	49 - 98
51-100	Optimum	Yield response unlikely	0 - 49	0 - 98
>100	Excessive	Yield response very unlikely	0	0

* Based on University of Maryland soil test categories (Coale, 1996)

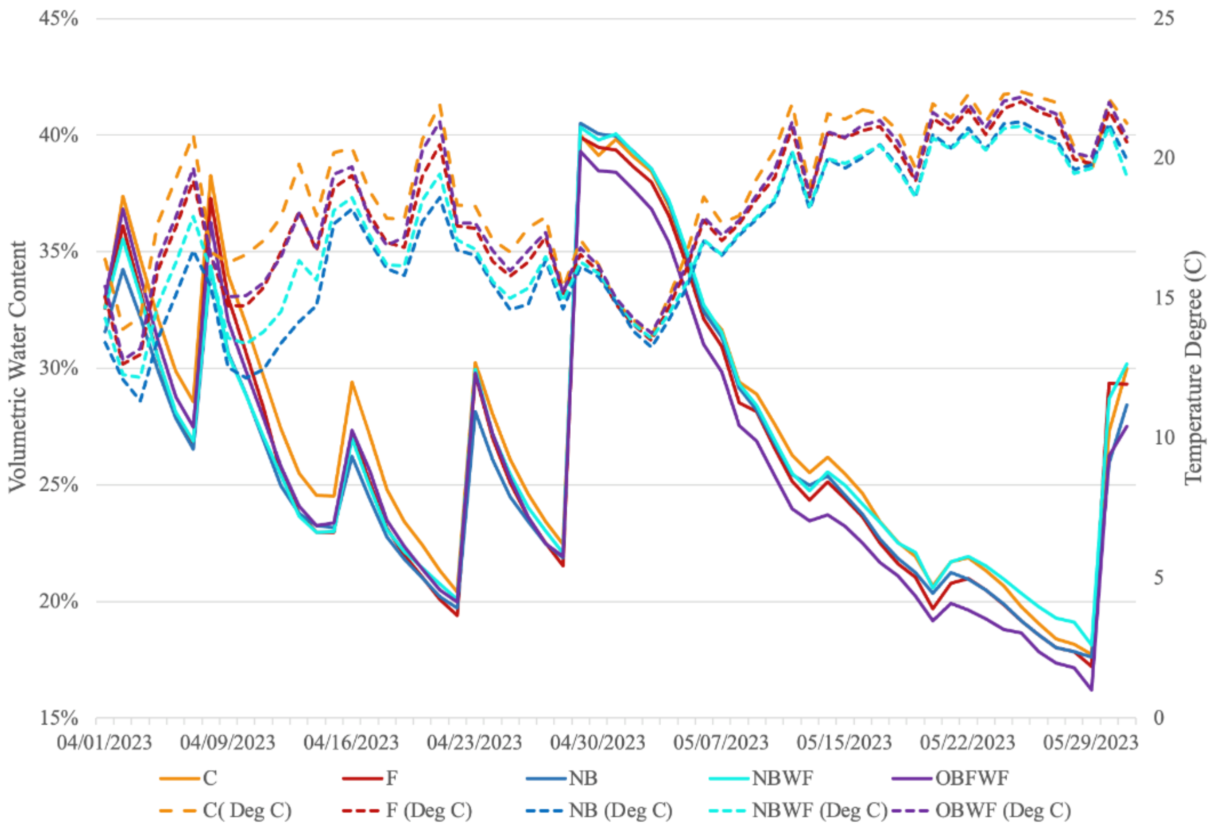
Appendix F

Field Study June Soil Nutrient Concentrations						
		Treatment				
		C	F	OBWF	NBWF	B
pH	Mean	5.85	5.82	5.96	5.76	5.64
	SD	.10	.15	.10	.13	.08
Soluble Salts	Mean	.10	.14	.14	.15	.24
	SD	.01	.01	.03	.02	.03
CEC	Mean	5.72	5.54	6.78	6.46	6.92
	SD	.51	.48	.23	.48	.43
OM	Mean	3.38	3.40	4.08	3.98	4.52
	SD	.15	.17	.13	.19	.19
NO3	Mean	4.16	3.66	3.28	4.72	6.92
	SD	.65	.30	.19	.93	1.62
NH4	Mean	6.10	5.54	6.30	7.52	7.70
	SD	.86	.66	.61	.54	.51
Mehlich-3 P	Mean	11.80	13.00	57.40	51.40	75.40
	SD	1.79	1.87	11.91	2.30	7.73
Fe	Mean	104.00	103.40	222.00	224.00	296.00
	SD	5.48	6.15	31.14	5.48	18.17
Al	Mean	684.00	674.00	684.00	672.00	674.00
	SD	29.66	36.47	37.82	30.33	25.10
Ca	Mean	675.60	644.00	857.00	777.20	817.60
	SD	76.74	79.73	38.54	83.40	65.16
S	Mean	6.40	7.20	11.80	18.80	33.00
	SD	.55	.45	1.48	2.59	6.04
Mn	Mean	122.00	116.80	100.00	92.40	87.40
	SD	13.04	21.94	11.51	15.66	7.89
K	Mean	91.80	88.40	93.60	76.00	64.20
	SD	7.46	7.50	9.96	11.60	6.87
Mg	Mean	124.60	120.80	136.80	127.40	123.40
	SD	17.27	19.41	7.12	20.11	14.57
B	Mean	.38	.38	.67	.67	.80
	SD	.04	.02	.05	.04	.06
Na	Mean	12.20	13.80	14.00	15.00	15.40
	SD	.45	1.10	.71	1.00	1.14
Zn	Mean	3.33	2.93	5.19	6.88	10.95
	SD	2.11	.75	.99	1.35	1.42
Cu	Mean	2.30	1.89	2.63	3.10	4.52
	SD	.40	.57	.53	.59	.90

Appendix G

Daily Minimum Volumetric Water Content and Maximum Temperature for the Field Study (4/01/22 – 5/29/23)

Note: Sensors were buried 5.08 cm below the surface. Additional details are described in 5.2.2 Field Study.



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