ABSTRACT

Title of Dissertation: **ASSESSING THE IMPACTS OF ORGANIC AMENDMENTS ON DISTURBED SOIL PROPERTIES, WATER QUALITY AND VEGETATION GROWTH**

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Deficiencies in essential organic matter (OM) are exhibited in disturbed roadside soils rendering them less favorable for plant growth. Vegetation plays a crucial role in maintaining the health of ecosystems, providing a myriad of benefits in protecting against soil erosion and effectively managing stormwater. National and state transportation departments are therefore prioritizing roadside vegetation using sustainable practices, leading to increased use of organic amendments (OAs) such as compost or related materials. OAs are commonly recycled and repurposed materials that serve as valuable soil conditioners, and their characteristics vary depending on their parent materials. Many OAs are cost-effective, readily available, and offer significant benefits to urban soils, which often are bereft of plant-essential nutrients and stability. This necessitates a better understanding of their impact on soil health and the environment, when applied at "acceptable" rates. This research aims to explore soil-water-plant interactions in urban soils (with and without OAs) focusing on vegetation establishment, soil fertility, and nutrient transport via leaching/runoff. Greenhouse and laboratory experiments were conducted to assess the potential use of these OAs for roadside projects.

One set of experiments (greenhouse tub studies) focused on three OAs (leaf compost, shredded aged wood mulch, biosolids) which are widely available across Maryland. The amended

soils were mixed to meet the topsoil OM requirements (4 – 8 %) of the state. Water quality results highlighted that the biosolids, while effective in retaining influent rainwater (tap water) phosphorus, caused significant nitrogen losses, exceeding typical stormwater concentrations by 40-200 times. Leaf compost also contributed to nitrogen leaching but only during the initial stages. Mulch reduced nutrient loss but caused limited vegetative cover. The study found that soil properties, such as the carbon-to-nitrogen (C:N) ratio and nitrogen content, play a vital role in the magnitude and patterns of nitrogen leaching. Additionally, it was speculated that the presence of soil minerals, such as iron and calcium, successfully retained phosphorus in the amended soils. The shear and hydraulic properties of the soils improved with the incorporation of amendments.

Based on the results of the tub studies, leaf compost identified as a suitable OA for plants and water quality. However, the tub studies had limitations in their evaluation of compost amendments derived from different feedstock sources and their impacts on native vegetation growth. Therefore, a pot study was conducted to determine the optimum mixing ratios of soils and OAs to facilitate rapid vegetation growth. Three types of composts (turkey litter, food waste and yard waste) with varying nutrient properties were tested. A wood-based biochar was the fourth chosen OA because of its valuable use in agriculture and environmental remediation. The findings showed that turkey litter compost severely inhibited growth at higher application rates due to excess salts content. However, this compost showed improved plant nitrogen and leaf area whenever vegetation was established. Alternatively, biochar, while not inhibiting growth, resulted in visibly weak plant morphology, and led to nitrogen deficiencies. Yard waste and food waste composts showed positive impacts in terms of coverage, leaf area index and plant N contents.

Between the tub studies and the pot study, yard waste compost has consistently emerged as the favorable soil amendment. Given biochar's well documented advantages for water quality

and soil structural properties, a scaled-up mesocosm experiment that simulated sloped road shoulders was conducted to test the effectiveness of combining compost and biochar in urban soils, aiming to meet vegetation and water quality goals. The runoff phosphorus and nitrogen mass transports were highest (261 mg-P/m^2 and 8645 mg-N/m^2, respectively) when compost was the sole amendment mixed into the control soil. However, adding biochar to the soil reduced these losses by up to 5.6x for phosphorus and 8.8x for nitrogen compared to compost. Strong correlation between soil C:N and effluent N was noted, higher ratios (>20:1) reduced nitrogen losses. Biochar, due to its high carbon content and pH, also helped retain phosphorus in the soils. Conversely, compost, being more readily decomposable than biochar, caused nutrients to run off. Compost-biochar mixtures also showed greater plant growth compared to the control soil.

Together, this research shows that not all high-nutrient OAs provide favorable outcomes when incorporated into soils to enhance the OM content. Leaf or yard waste-based composts are preferred for roadside vegetation due to their reduced issues related to nutrient losses compared to other nutrient-rich materials tested in this study. However, the yard waste compost incorporation rate should be limited to achieve a soil OM increase of 1-2% to prevent high nutrient levels in the runoff. Furthermore, combining biochar and yard waste compost offers a promising approach for construction projects particularly on steep terrains to achieve and preserve a balanced soil-water-plant ecosystem.

ASSESSING THE IMPACTS OF ORGANIC AMENDMENTS ON DISTURBED SOIL PROPERTIES, WATER QUALITY AND VEGETATION GROWTH

by

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Dissertation submitted to the Faculty of the Graduate School of the
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Dedication

To Nanna, for envisioning and empowering my dreams.
To Amma, for her selfless and steadfast support.
To Annayya, for blazing the trail and paving the way forward.
To Baba, for being my life force and inspiring me to work for the greater good.

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Embarking on a PhD journey is not an easy sail; it is a blend of lasting labs, trudging troughs, manuscript marathons and euphoric eurekas. As I reflect on this journey, I am eager to express my gratitude to everyone that helped me get to the finale.

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Making new friendships as grown-ups is a struggle, but it happened to me in College Park. The cherished memories of dinner nights, board games, birthday cakes, shared laughter, and tears in our humble 8909 with Harshithaa, Shshank and Sid will forever remain etched in my heart. Rama and Saranya were always a call away to recalibrate and restabilize me. Their encouragement kept me motivated throughout this difficult journey, and they believed in me with complete sincerity. Stephanie, a constant and kind friend, has always been inspiring. I deeply admire her work ethic, and her friendship holds a special place in my heart. Among other friends who are like family are Pinku, Bittu, KC, Shiva, Krittika, Vidya, and Uma. They were patient with me, kept me in their thoughts, and wished nothing but the best for me. I have been fortunate to have this kind of support system.

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My last memory with L.S.P.V. Krishna Reddy (Mamayya)
and L. Kamakshi (Attamma) together

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List of Abbreviations

Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
BMP	Best Management Practice
CEC	Cation Exchange Capacity
C:N	Carbon to Nitrogen
DOC	Dissolved Organic Carbon
DON	Dissolved Organic Nitrogen
DOP	Dissolved Organic Phosphorus
DOT	Department of Transportation
EC	Electrical Conductivity
LRRB	Local Road Research Road
MDOT	Maryland Department of Transportation
MnDOT	Minnesota Department of Transportation
MSU	Michigan State University
NH_4	Ammonia
NO_3	Nitrate
NO_2	Nitrite
NO_x	Nitrate + Nitrite
OA	Organic Amendment
OM	Organic Matter
PP	Particulate Phosphorus
QA/QC	Quality Assurance/Quality Control
SHA	State Highway Administration
SRE	Simulated Rain Event
SRP	Soluble Reactive Phosphorus
STDEV	Standard Deviation
TN	Total Nitrogen
TDP	Total Dissolved Phosphorus
TP	Total Phosphorus
TSS	Total Suspended Solids
UMD	University of Maryland
USCS	Unified Soil Classification System
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency

CHAPTER 1. INTRODUCTION

Inadequate fertility in the topsoils of road- and highway- shoulders and embankments may yield underwhelming vegetative cover. The lack of a robust plant root system disrupts soil integrity and disposes it to erosion and increased surface runoff, especially on slopes (Donn et al. 2014). Intense rainfall or snowmelt can mobilize pollutants from the degraded soils into surface or stormwater runoff, ultimately transporting these pollutants into nearby natural water bodies (US EPA 2015c). Undesirable changes in ecosystems can occur as more nutrients get accumulated in the water resources, leading to dense algae layers on the water's surface (US EPA 2013c). Consequently, this can result in the formation of oxygen-depleted "dead zones", thereby adversely affecting aquatic organisms (Conley et al. 2009). This phenomenon is known as eutrophication and constitutes a significant concern associated with stormwater pollution. Similar to nutrients, trace metals (such as Cu and Zn) and organic pollutants can also be carried into the water bodies via sediment, posing aquatic toxicity and potentially causing fish kill (McCarthy et al. 2008).

Recycled organic materials or organic amendments (OA) are being introduced into soils as a means to remediate low-quality urban soils for several compelling reasons, including the promotion of healthier plant growth and the enhancement of soil structure (Donn et al. 2014; Owen et al. 2021). In the United States, transportation departments (DOTs) in several jurisdictions commonly use composts and wood mulches along highways either as a blanket on the soil surface or amended into soils (e.g., MDOT SHA 2018). The porous nature of these organic amendments brings several advantages, including improved water retention capacity, reduced bulk density, increased hydraulic conductivity, and enhanced strength in soils (Kranz et al. 2020; Duzgun et al. 2021).

Organic amendments come in many forms, of which the most commonly used ones that improve the organic matter (OM) content of soils are discussed below. These OAs are essential tools both in agriculture and horticulture practices, often replacing synthetic fertilizers and contribute to a more environmentally friendly land management.

Compost: Composting is an age-old environmental practice where organic waste is recycled into a stable agricultural product under controlled aerobic conditions (US EPA 2015d). The types of compost can be categorized based on their waste source. Specific compost properties depend on the feedstock elements and compost maturity. Irrespective of the feedstock elements, composted products have shown to be effective soil amendments by improving soil fertility, crop yield, infiltration rate, and porosity (Kranz et al. 2020). Fundamental feedstock elements of leaf compost are yard wastes, such as leaves, grass clippings, leftover gardening or plant debris, and weeds (US EPA 2015d). Shredded wood scraps are also included in finite quantities to boost the carbon content of the compost in order to strike an optimum balance of the carbon to nitrogen (C:N) ratio. Leaf-based compost is seasonal, and the properties depend on its primary ingredients during that season (e.g., more leaves are composted around fall, and more yard waste and grass clippings are composted during summer).

Alternatively, food waste compost is derived from composting food scraps or kitchen waste. As of 2018, 24.1% of the generated food waste was disposed of in landfills (US EPA 2017). Therefore, a shared national goal was set between the United States Environmental Protection Agency (EPA) and the United States Department of Agriculture (USDA) to reduce 50% of the food waste production by 2030 (US EPA 2016a; USDA 2015). Since 54.1% of the food waste contains compostable material (MDE 2021), one of the pathways to reduce food waste is through composting. Typically, a portion of yard waste is also combined into the food waste compost pile to account for both “greens” (nitrogen derived from food and grass) and “browns” (carbon derived from dry leaves and branches) (US EPA 2015d). Either of the composts, depending on their quality, offer numerous benefits to the soil: improved soil porosity, increased water retention capacity, buffering soil pH, and providing plant essential nutrients (Kranz et al. 2020).

Although not a popular choice, animal manure composts are used as soil amendments that have proven to add organic matter and supply essential nutrients to the soil needed for plant establishment. With growing production of livestock, recycling animal waste can not only provide benefits to the agriculture sector as a natural fertilizer, but also in the energy sector through use in biogas synthesis (US EPA 2020). Direct application of raw manure, without any pretreatment steps, can be detrimental to the environment, as excessive nutrients change forms from their organic to reactive species (e.g., N changing from organic nitrogen to ammonia (NH_3) or nitrate (NO_3)) and become susceptible to leaching. Therefore, manure is typically stabilized for organic matter through composting, and treated with chemical additives such as alum to curb NH_3 losses to the atmosphere, prior to land application (Szogi et al. 2015).

Biosolids: Biosolids are a product of the sewage treatment process; they are nutrient-dense and can be land-applied to improve soil fertility and crop yield. Roughly 4.5 million dry metric tons of biosolids was produced in the United States in 2021 of which 43.5% was land applied and 1.3% was spent in other management practices, with the remainder being either incinerated or landfilled (US EPA 2022a). Biosolids is classified into “Class A” and “Class B” according to the EPA’s federal regulation 40 CFR Part 503 (US EPA 2016b). “Class A” biosolids is a preferred soil amendment or conditioner as it is a stabilized product (humus-like) with high nutrient value and undetectable pathogen concentrations. Composted biosolids contain high levels of beneficial macro nutrients (nitrogen, phosphorus and potassium) and micro nutrients (zinc, copper, iron) that aid in plant establishment (Cheng et al. 2007). A few limitations to using biosolids extensively are its high soluble salts content, odor, and probable ammonium and heavy metal pollution (Linde and Hepner 2005) .

Mulch: Ingredients for mulches that are biodegradable include wood chips, brushy wood material, straw, and tree bark (Sullivan and Scheetz 2005). Grass clippings or leaves are also added to organic mulches, in less amounts. A total of 13 soil producers were surveyed in the state of Maryland by Morash (2024) to learn about the organic amendments they use in order to meet the topsoil OM requirements of 4 – 8% as listed in MDOT SHA (2017). The survey results revealed that mulch is another form (next to leaf compost) of soil amendment that is preferred by the soil producers to increase their soil OM content due to its wide-spread availability (Morash 2024). Mulches can increase the carbon content of soil, greater cation exchange capacity, improve infiltration, reduce erosion, and improve water quality (Jang et al. 2005). Wood derived OAs contain plenty of carboxylic and hydroxyl functional groups that can retain stormwater pollutants, particularly trace metals (Hopkins et al. 2021).

Biochar: Another carbon-rich organic material that is of keen interest in recent years is biochar. It is produced by thermal combustion of biomass in an oxygen-deficit environment in a process called “pyrolysis” (Lehmann et al. 2011; Oni et al. 2019). The structure and stability of the biochar product depends on its feedstock sources (e.g., animal manure, straw biomass, wood waste, agricultural waste, food waste), pyrolysis temperature, and heating rate (Kaya et al. 2022). Biochar addition has proven to be an effective soil remediation strategy, improving soil porosity, adsorbing inorganic and organic contaminants, and enhancing stormwater quality (Oni et al. 2019; Ulrich et al. 2015).

In the context of vegetation, extensive research has been conducted to explore the effects of OAs on soil fertility. Kranz et al. (2021) observed greater turf growth with an increasing rate of compost addition over a 5-week period. Another study, which evaluated 9 different composts concluded that manure-based composts resulted in the largest plants compared to green-waste and food scraps composts (Heyman et al. 2019). The effect of biochar on plant growth can vary significantly, depending largely on the source materials used to produce the biochar (Ding et al. 2016). Its impact can either enhance or negatively impact vegetation growth, contingent upon nutrient availability. For example, sewage sludge-biochar when mixed into an urban soil improved the soil nutritional value and produced a notable increase (43-147%) in the turf biomass (Tian et al. 2019). A comprehensive review that summarized 634 biochar-related soil fertility research articles noted that wood-based biochar can result in lower nutrient availability compared to manure or leaf biochar (Agegnehu et al. 2017).

In soils, N can undergo various transformations through many microbial mediated pathways when vegetation is being established (Galloway 1998). N is commonly supplemented to the soils in the form of fertilizers or through OAs. One of the initial transformations is when the organic nitrogen ($R\text{-}NH_2$), from the OA, gets mineralized under aerobic conditions into plant available or biologically reactive forms (NH_4^+ and NO_3^-) via ammonification (conversion of $R\text{-}NH_2$ to NH_4^+) and nitrification (conversion of NH_4^+ to NO_3^-) (Fig. 1-1). The microbes responsible for ammonification are called decomposers and the ones mediating nitrification are known as the nitrifying bacteria. With plant growth, the soil concentrations of $R\text{-}NH_2$ and NH_4^+ tend to reduce while NO_3^- increases (nitrification driven process) (Fig. 1-1). Since clay and organic matter in soil media are negatively charged, and NO_3^- is anionic, the latter cannot adsorb onto the media and can become mobile (Lehmann and Schroth 2002). Depending on the organic sources present in the soil, prior to any vegetation growth, the predominant forms of N in soils would likely be R-NH_2 and/or NH_4^+. For example, manure-based OAs contribute to high ammonia leaching compared to green waste or wood mulch-based materials (Heyman et al. 2019). N in agroecosystems is not just carried away by water via leaching, it can also be volatilized and escaped into the atmosphere as gaseous N_2 (non-reactive form) via biological denitrification (Galloway et al. 2003).

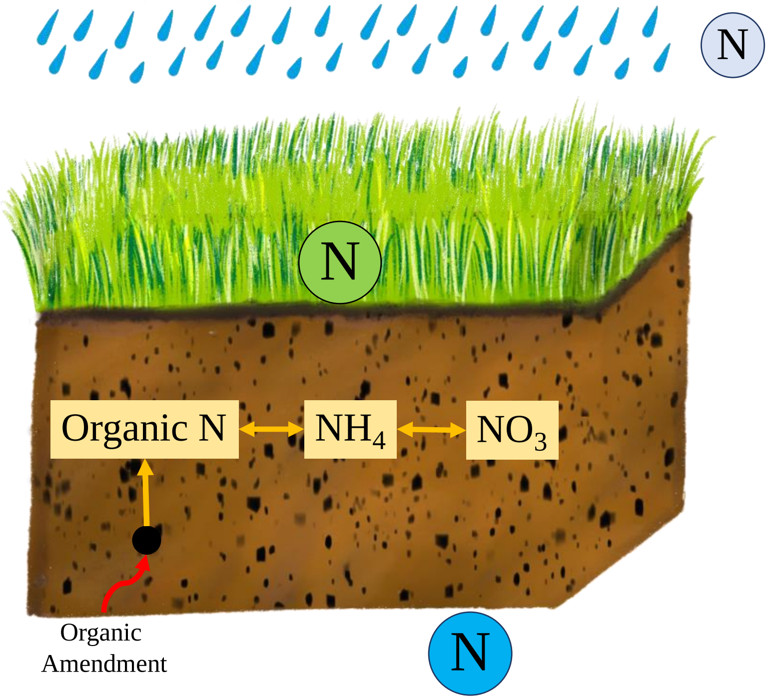

Fig. 1-1. *Dominant nitrogen pathways in organic soils*

Similar to that of N, P undergoes several complex biogeochemical interactions within the soil matrix. The organic forms of P from OA additions are mineralized into soluble reactive P or orthophosphate (OP; forms: $H_2PO_4^-$ or HPO_4^{2}) by phosphorus solubilization microbes. OP can either be taken up by plants, leached or can be immobilized by soil components such as mineral oxides or hydroxides via adsorption (ligand exchange) (Fig. 1-2). For example, P fixing capacity within the soils will inversely depend on soil pH and is directly related to iron and aluminum contents (Gupta et al. 2020). The effects of soil pH on P availability and solubility is discussed at length in an interpretative review by Penn and Camberato (2019), seconding the hypothesis by Price (2006) that the optimum “valley” for soil pH is between 6 – 7 (near neutral), where the forms are orthophosphate are most available or mobile (Fig. 1-3. Phosphorus fixation in soils by iron, aluminum, and calcium under varying soil pH conditions. Figure. Under low soil pH conditions, there is preferential adsorption of P by the Al/Fe minerals and at higher than neutral pH, P is complexed with Ca minerals (Price 2006). This indicates that P losses to infiltrated waters will be minimal given the presence of soil minerals and the availability of P in such a narrow pH range. Based on the type of OA applied, P can be retained or leached in the soils. Qi et al. (2023) noticed that biochar application minimized P leaching from paddy fields. Conversely, compost-like materials are reputed for transporting soluble P from soils, particularly when applied at elevated rates (Owen et al. 2021, 2023; Davis et al. 2023).

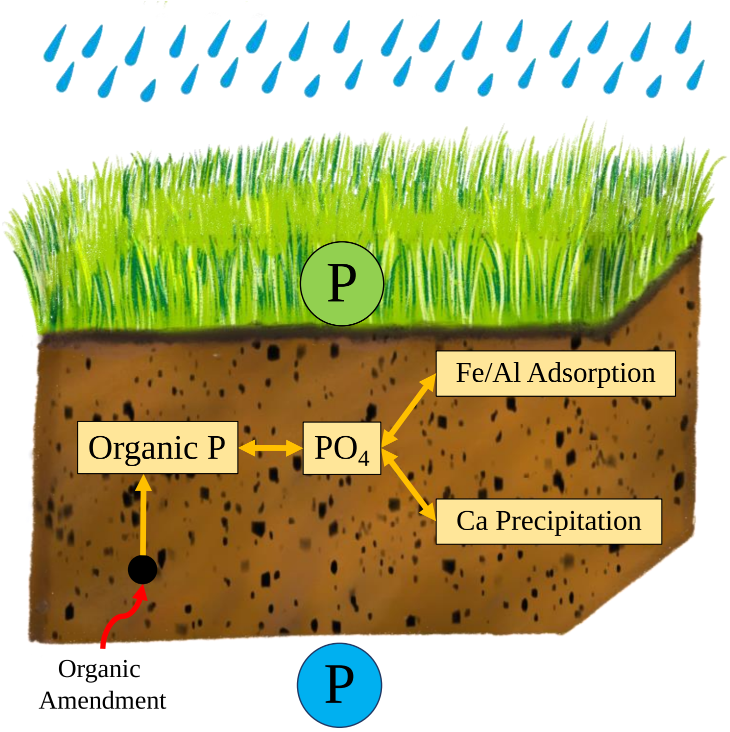

Fig. 1-2. *Dominant phosphorus pathways in organic soils*

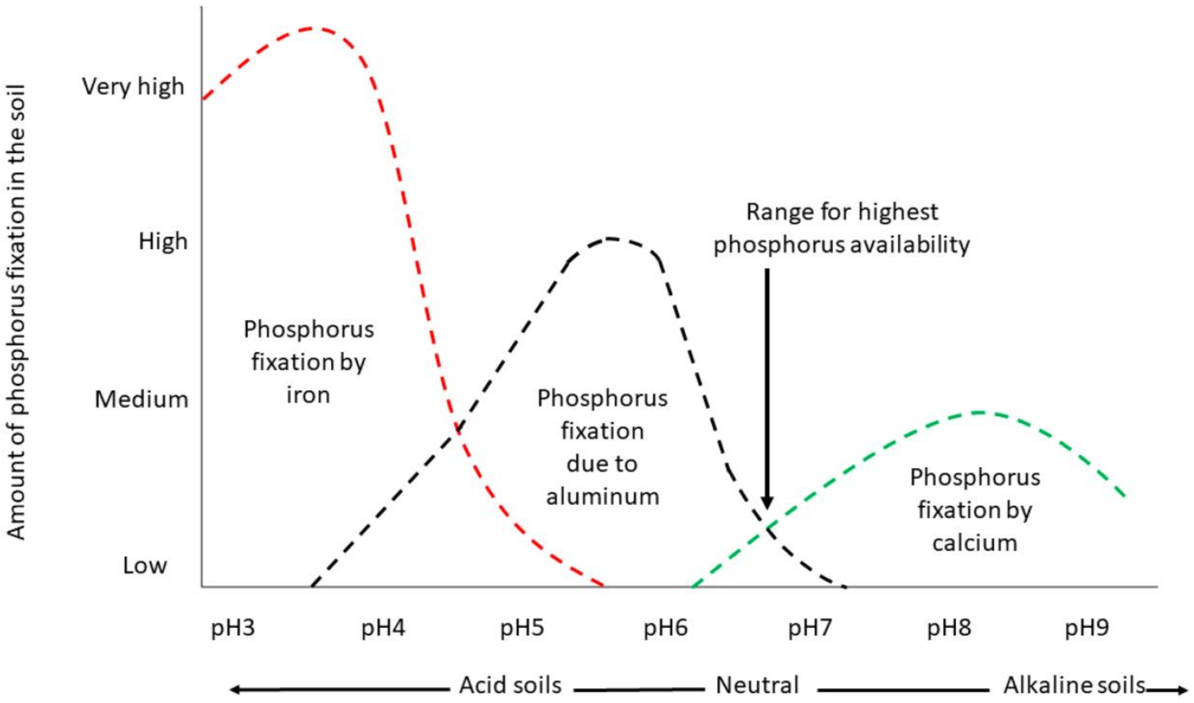

Fig. 1-3. *Phosphorus fixation in soils by iron, aluminum, and calcium under varying soil pH conditions. Figure adapted from Price (2006), redrawn by Penn and Camberato (2019).*

Organic amendments play a pivotal role in strengthening soil by improving structure, texture, and water-holding capacity. Influences of OAs such as biochar and composts on shear properties of soils from various studies are presented in Table 1-1. Hussain and Ravi (2022) evaluated hard wood-derived biochar on pure and silty sands at different application rates of the amendment. A statistically significant increase ($p < 0.05$) in cohesion (c') was noticed due to the addition of biochar in both sands, with greater amendment effects on the silty sand due to the presence of clay fines compared to pure sand. The internal friction angle (□'), however, was only increased in the silty sand, but not pure sand. The higher frictional resistance of pure sand compared to biochar may have lowered □' in the amended sand. Similar findings were reported by the same authors in their preceding article (Hussain et al. 2021), where biochar amendment improved the ductility and shear strength properties of the clayey soil under the applied normal loads and shearing. Sadasivam and Reddy (2015) conformed these observations in their research as well. On the contrary, Zong et al. (2014) noted a significant ($p < 0.05$) increase in □’ and a decrease in c’ in soils as affected by the biochar amendments. However, the study encourages the use of biochar as a potential amendment due to the improvement noticed in tillage and desiccation cracks of a clayey soil.

The presence of organic matter (biosolids and dairy manure), added at levels below 30%, enhanced resistance to shrinkage and an increase in shear strength of expansive clays (Puppala et al. 2007). In a more recent study, through rigorous direct shear and tri-axial shear testing procedures, the effect of compost addition on soil properties was determined (Duzgun et al. 2021). Compost addition was associated with a notable increase in cohesion, indicative of improved internal strength and resistance to soil deformation. Donn et al. (2014) showed that the impact of green compost on shear parameters (c’ and ϕ’) under the applied rates was minimal ($p > 0.05$) However, it was observed that, over an extended timeframe, the presence of a reinforced root system due to the vegetation growth yielded an increase in peak shear stress within the soil. In summary, these scientific inquiries underscore the positive contributions of compost amendments to soil engineering properties, particularly in terms of shear resistance, cohesion, and friction angle. Furthermore, the influence of vegetation on soil shear strength warrants considerations for use of OAs in soil stabilization strategies.

Table 1-1. Effects of Organic Amendments on the Shear Properties of Soils

Control Soil	Amendment	Amendment Feedstock	Shear Properties		Reference
			Cohesion (c')	**Friction Angle (ϕ')**	
Pure Sand	Biochar	Hardwood	Increased	Decreased	Hussain and Ravi (2022)
Silty Sand	Biochar	Hardwood	Increased	Increased	Hussain and Ravi (2022)
Clayey Sand	Biochar	Hardwood	Increased	Increased	Hussain et al. (2021)
Soil (< 2mm)	Biochar	Wood Waste	Increased	Increased	Sadasivam and Reddy (2015)
Clay	Biochar	Wheat Straw	Decreased	Increased	Zong et al. (2014)
Clay	Biochar	Wood Chips	Decreased	Increased	Zong et al. (2014)
Clay	Biochar	Wastewater Sludge	Decreased	Increased	Zong et al. (2014)
Sandy Loam	Compost	Leaf	Increased	Increased	Duzgun et al. (2021)
Sandy Loam	Compost	Biosolids	Increased	Increased	Duzgun et al. (2021)
Silty Sand	Compost	Plant Residues	Unchanged	Unchanged	Donn et al. (2014)
Lean Clay	Compost	Biosolids	Increased	Increased	Puppala et al. (2007)
Lean Clay	Compost	Dairy Manure	Increased	Increased	Puppala et al. (2007)

The incorporation of OAs into soils is recognized for increasing the soil organic matter content, a crucial factor for facilitating optimal plant growth. However, it is imperative to regulate the quantity (not over fertilize) added to prevent excess leaching of nutrients (nitrogen or phosphorus), fluctuations in soil pH, and soluble salts imbalances. Many DOTs in the US stipulate that the OM content in topsoil should fall within the range of 3 – 15%, with certain states imposing even stricter criteria. For instance, the Maryland Department of Transportation State Highway Administration (MDOT SHA) mandates that the furnished topsoil products possess an OM content of 4 – 8% to qualify for use on state roads and highway projects (MDOT SHA 2017a).

Moreover, there is a growing interest among various DOTs in the application of compost or compost-like materials as amendments to meet their soil OM prerequisites. This necessitates a deeper understanding of the roles played by these materials in the overall soil health, while concurrently mitigating potential environmental impacts, particularly in relation to stormwater pollution. In addition, the body of literature addressing the geotechnical attributes of soils blended with organic amendments is relatively sparse. Understanding shear properties under field conditions is pivotal for assessing the requisite soil strength in the context of slope stability.

The objective of this study is to undertake a comprehensive investigation of diverse soil types that have been amended with a range of organic materials, including composts, biosolids, mulch and biochar. This multifaceted analysis included an assessment of vegetation growth, as well as an evaluation of water quality parameters (N, P and metals) in runoff/leachate. Additionally, the study also tested for geotechnical properties, specifically focusing on shear strength and hydraulic conductivity of the amended soils. The overarching goal of this study is to explore the potential applications of these modified soils on road shoulders. The research methodology involved a series of controlled experiments conducted in the University of Maryland's (UMD) research greenhouse facility. Three experiments were designed to meet the overall research objective:

Experiment 1: Nutrient Transport, Strength, and Hydraulic Characteristics of Topsoils amended with Compost, Mulch and Biosolids

- *Objective: Determine nutrient leaching characteristics, and engineering (shear and hydraulic) properties of amended soils to identify OA(s) that perform well in the nexus of soil strength-vegetation establishment-water quality.*

Experiment 2: Optimizing Native Vegetation Establishment in Urban Soils: Assessing the Impacts of Organic Amendments on Specific Growth Parameters

- *Objective: Determine the optimum ratios of soil and OA that provide soil nutrient needs required for rapid plant establishment and growth.*

Experiment 3: Performance of Compost-Biochar Amended Soils with respect to Vegetation, Water Quality, and Hydraulic Properties

- *Objective: Test the synergistic effectiveness of compost-biochar mixtures in reducing nitrogen and phosphorus leaching, and in improving vegetation growth and quality.*

Across the three experiments, a total of 6 organic amendments were examined. The first experiment focused on analyzing the nutrient and metal release in two greenhouse mesocosm tub studies of topsoils mixed with *aged wood* mulch, *leaf* compost, and *stabilized sewage sludge* or biosolids. The study also assessed shear and hydraulic properties of these topsoils through lab-based testing. The second experiment is a pot study that evaluated the effects of three composts *(derived from yard waste, food waste, turkey litter)* and one *wood-derived* biochar on plant establishment, considering factors such as green coverage, leaf area, nitrogen uptake and biomass. Finally, based on the findings of experiments 1 and 2, the third study involved exhaustive examination of *yard-waste* compost and *wood-derived* biochar mixtures on nutrient water quality, water retention, and plant growth in a 13-week scaled up pilot study that replicates field conditions.

CHAPTER 2. NUTRIENT TRANSPORT, SHEAR STRENGTH AND HYDRAULIC CHARACTERISTICS OF TOPSOILS AMENDED WITH MULCH, COMPOST AND BIOSOLIDS

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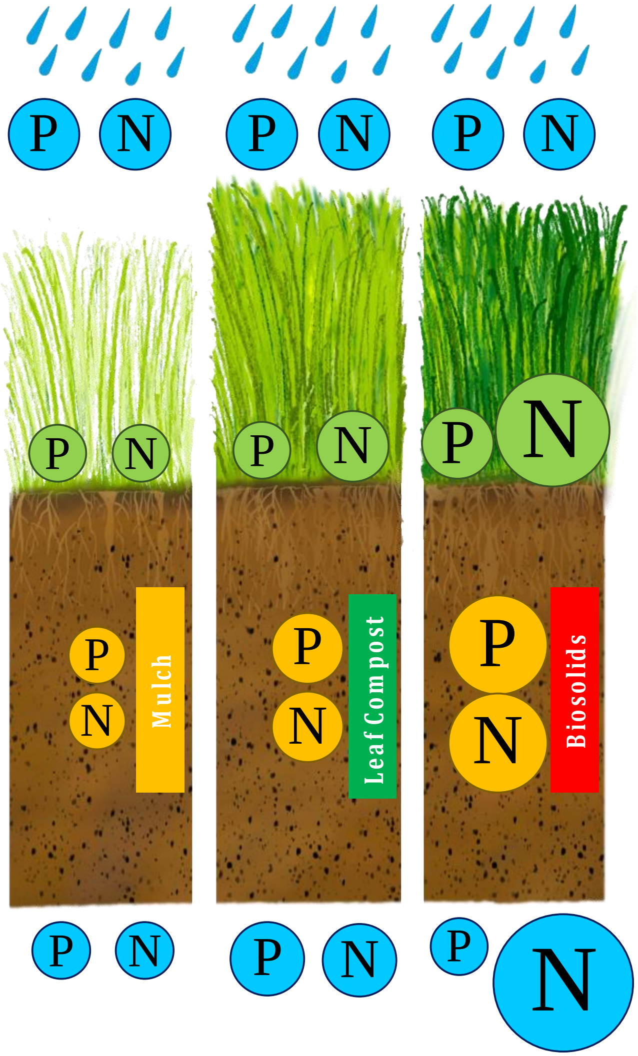
Abstract

Anthropogenic disturbance of soils can disrupt soil structure, diminish fertility, alter soil chemical properties and cause erosion. Current remediation practices involve amending degraded urban topsoils lacking in organic matter (OM) and nutrition with organic amendments (OA) to enhance vegetative growth. However, the impact of OAs on water quality and structural properties at rates that meet common topsoil OM specifications need to be studied and understood. This study tested three commonly available OA's: shredded wood mulch, leaf-based compost, and class A Exceptional Quality stabilized sewage sludge (or biosolids) for nutrient (nitrogen and phosphorus) water quality, soil shear strength, and hydraulic properties through two greenhouse tub studies. Findings showed that nitrogen (N) losses to leachate were greater in the biosolids amended topsoils (BAT) compared to leaf-compost and mulch amended topsoils (LAT and MAT) and control (CUT) treatments. Steady-state mean total N (TN) concentrations from BAT's exceeded typical highway stormwater concentrations by at least 25 times. Soil TN content combined with the C:N ratio was identified to be the governing properties of N leaching in soils. Study soils, irrespective of the type of amendment, reduced the applied (tap) water phosphorus concentration of ~0.3 mg-P/L throughout the experiment. Contrary to the effects on N leaching, P was successfully retained by the biosolids amendment, due to the presence of greater active iron (Fe) contents. A breakthrough mechanism for P was observed in CUT and LAT soils, where the effluent concentrations of P continued to increase with each rainfall application, possibly due to an oversaturation of soil adsorption sites. The addition of OAs is shown to improve the strength and hydraulic properties of soils. The effective interlocking mechanisms between the soil and OA surfaces could provide soil its required strength and stability, particularly on slopes. OAs also improved soil fertility to promote turf growth. Presence of vegetative root zones can further reinforce the soil and control erosion.

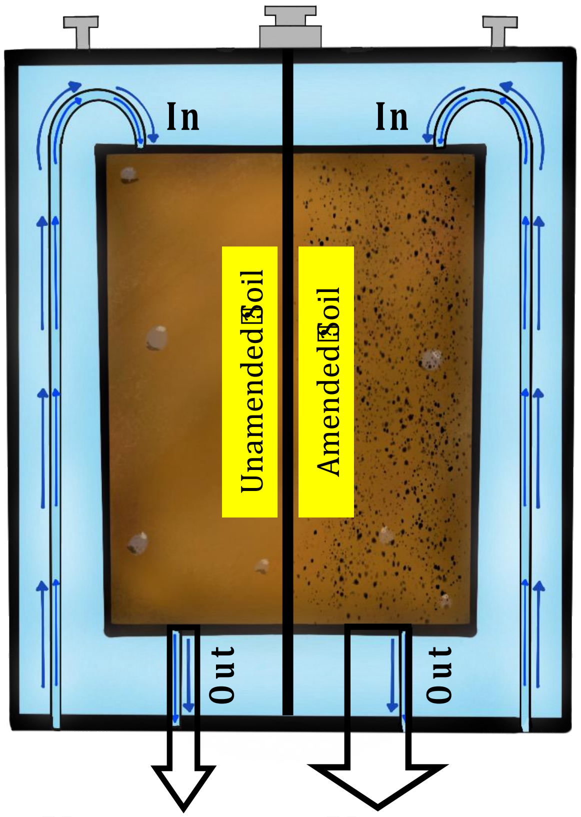
(Keywords: Soils, Organic amendments, Nitrogen, Phosphorus, Nutrient Leaching, Shear, Hydraulic Conductivity)

Highlights

- Different types of organic amendments positively influenced shear and hydraulic properties of soils.
- Nutrient transport in soils differed depending on the organic amendment used.
- Biosolid application improved phosphorus retention in soils, while it incurred nitrogen losses.
- Holistically, leaf-based compost was identified as the preferred organic soil amendment for use in roadside projects.
- Evidence-based recommendations for the use of OAs are provided.



P was effectively retained in the soil by all OAs
N retention was observed only through mulch
and leaf-compost, but not biosolids



$K_{\text{sat (unamended)}} < K_{\text{sat (amended)}}$

Addition of OAs improved
saturated hydraulic conductivity (K_{sat})

Introduction

A direct effect of urbanization and human activity is evident in the declining physical and chemical properties of urban soils particularly those along roads and highways. Grading, compaction, and other disturbances associated with roadside construction activities can damage the soil structural functionality (Gray and Sotir 1996). Topsoil or subsoil is often left bare, which predisposes it to erosion during rain events and discharges heavy loads of sediment and pollutants (e.g., nutrients and trace metals) into downstream waterbodies (such as the Chesapeake Bay) via stormwater runoff. Nutrient-rich waters enhance algae growth, resulting in eutrophication and hypoxia (US EPA 2015a). These urban soils are often low in organic matter and both macro- and micronutrients, structurally unstable, and inhospitable for vegetation (Heyman et al. 2019). To counter this situation, many jurisdictions are opting for more sustainable and less expensive soil treatments, such as amending with composts and biosolids (a byproduct of wastewater treatment), which when incorporated into urban soils provide some nutrition, and promote water retention and infiltration (Kranz et al. 2020; Owen et al. 2021).

According to the U.S. EPA, in 2018, 2.2 kg/day of Municipal Solid Waste was generated per capita (US EPA 2022b). Approximately 50% of this waste was either recycled, composted, combusted with energy recovery, or utilized for other food management techniques (US EPA 2022b). This suggests that there is a recoverable fraction of available compost and other organic materials that could be used in lieu of expensive and potentially unsuitable commercial fertilizers for promoting vegetative growth on marginal soils. Since the early 2000s, compost materials have been sought-after by many U.S. state Departments of Transportation (DOTs) for their potential to enhance soil quality. Associated research continues to show beneficial effects when they are mixed with low-grade urban soils due to the addition of organic matter (OM) and nutrients to the soil, which improves soil fertility and thereby prevents erosion alongside roads and highways (Batjiaka 2016).

In July 2020, our research team interviewed topsoil blend producers across Maryland (Morash 2024). Among the soil amendments that meet the Maryland State Administration Department of Transportation State Highway Administration (MDOT SHA) furnished topsoil requirements for OM content of 4 – 8% (MDOT SHA 2017b), the top two preferred amendments were leaf or yard waste-based compost and wood mulch, due to their cost and availability. Outside of Maryland, biosolids are a popular roadside soil amendment due in part to efforts by the U.S. EPA to endorse the use of Class A Exceptional Quality (EQ) biosolids as a fertilizer for commercial and residential use without any special permitting requirements.

Nonetheless, excess application of OAs to soil can have adverse effects when it comes to nutrient leaching. For example, biosolids are one of the most abundantly produced and available organic materials, yet they typically contain high levels of leachable macro nutrients (N and P) (Paramashivam et al. 2016; Silveira et al. 2019) and toxic metals (Cd, Cu, Pb, Zn) (Torri and Corrêa 2012; Marguí et al. 2016). Puppala et al. (2011) assessed runoff leachate quality from topsoil amended with dairy-manure compost and biosolids and found that total phosphorus and total Kjeldahl nitrogen were high in the amended topsoils compared to the control. Similarly, Owen et al. (2021) noted greater P-losses from both green-waste (e.g., leaf compost) and biosolids composts compared to the unamended topsoil. Previous studies also indicated that leaching characteristics of soils depend on the compost source material (Hansen et al. 2012; Owen et al. 2021). This loss of N and P to surface waters can impair downstream waterbodies and worsen eutrophication. Excess soil nutrients from organic amendments, especially nitrogen species, have the potential to infiltrate through the soil profile and affect groundwater quality (a possible potable water issue). Caution should therefore be exercised, and an instructive investigation should be carried out to understand the leaching potential of compost amendments when mixed into topsoils.

Selecting (amended) soils with stable structure, increased soil porosity, decreased bulk density, and increased water retention capacity for highway or road slopes, particularly those with steep embankments, is vital for alleviating soil erosion and stormwater drainage/quality issues, and promoting vegetative growth. Although the physical and chemical characteristics of urban soils have been studied extensively, many other important variables will control stability, erosion, and vegetative growth. Knowledge of shear properties can help evaluate the strength of soils, which is indispensable in the context of sloughing or shallow infinite failures (Singh and Thompson 2016; Zheng et al. 2020). Only a few works (Benson and Othman 1993; Puppala et al. 2007; Duzgun et al. 2021) have focused on soil geotechnical properties when mixed with organic materials such as compost. This study aimed to close this gap and further contribute to the existing database of shear properties related to amended topsoils. As transportation authorities take measures to remediate or stabilize degraded soils through chemical additives or low-impact treatments, such as the addition of organic matter amendments, the effects on geotechnical properties should be investigated alongside other physical and chemical properties for a more holistic assessment.

The objectives of this study were to (1) compare soils amended independently with shredded wood mulch, leaf-based compost, and biosolids for nutrient contents in leached water, and geotechnical properties (shear and hydraulic), and (2) identify critical soil parameters that govern nutrient leaching dynamics from amended soils. Collectively, this information is useful in evaluating the performance of traditionally used organic amendments in the nexus of soil-water-vegetation and recommend their use for highway projects.

Experiment and Analytical Methods

Two macrocosm ‘tub’ studies (TS1 and TS2) were conducted at the University of Maryland Research Greenhouse Complex to monitor vegetation growth and water quality of unamended and amended topsoils. This work focuses on the water quality and geotechnical properties of the topsoils used in the tub studies; the effect of these characteristics on the vegetative growth, nutrient uptake and overall suitability are provided in Morash (2024).

Tub Study Soils and Organic Amendments

Based on the indicated preference by Maryland topsoil producers for either composted yard waste or a finely ground wood waste as an amendment (Morash (2024), TS1 and TS2 focused on these topsoil mixes. Given its broad availability in the Maryland/Washington DC area and its verified reputation for improving soil fertility, the tub studies also included Fresh Bloom® (EPA Class A Exceptional Quality Biosolids) as the third amendment of interest. Thus, each study included: Control Unamended Topsoil (CUT), Mulch Amended Topsoil (MAT), Leaf compost Amended Topsoil (LAT), and Biosolids Amended Topsoil (BAT).

Tub Study 1 (TS1) Soils: The research team sourced CUT1, MAT1 and LAT1 directly from MDOT SHA-qualified topsoil producers. BAT1 however was custom-made by the research team. The soil for BAT1 was obtained from a qualified topsoil producer and biosolids (Fresh Bloom®) was added to raise the OM content of the soil by approximately 1% to meet the MDOT SHA minimum OM concentration standard (4%).

Tub Study 2 (TS2) Soils: The soils used in each treatment in TS1 came from *different* producers and thus had varied physical and chemical properties. To determine the effects of each organic material, the base soil in TS2 was kept constant across all the treatments. The unamended base (control) soil (CUT2 at 4.34% OM) came from a Maryland SHA qualified soil producer. The base soil was then separately amended with finely shredded and aged tree mulch (M), composted leaves and grass clippings (L; Leafgro®, Maryland Environmental Services), and biosolids (B; Fresh Bloom®, DC Water), yielding MAT2, LAT2 and BAT2 respectively. After determining the concentration of OM in each amendment, enough was added to increase the OM content of the soil by 1-2%.

Tub Study Setup (Design and Water Collection)

Sixteen transparent plastic tubs (0.51 m x 0.74 m) were designed and constructed to accommodate four topsoil treatments with quadruplicates (Morash 2024). Fig. 6-1 shows a constructed tub system on a 4% inclined (25H:1V engineering slope) wooden frame that enabled the separate collection of surface runoff and leachate. For water to percolate freely, a meshed screen was placed inside the tub, overlain with a permeable green roof *Separation Fabric* (Conservation Technology, Baltimore, MD). Topsoil was spread to a depth of 10.2 cm on top of the fabric in each tub. 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%) was applied to each tub at a rate of 22.2 g/m^2 (~8.32 grams of seed mix per tub). Wheat straw was scattered over the soil after seeding to ensure the simulated rainwater treatments were evenly distributed over the tub soil surface.

A rainfall simulator (Fig. 6-1) was made by drilling 1 mm holes into a 0.51 m x 0.74 m plastic tub. The rainfall simulator produced 2.54 cm rainfall at an intensity of 10.2 cm/hr using tap water. A total of 20.3 cm rainfall over 8 weekly events were simulated during TS1 and a total of 22.9 cm rainfall (9 weekly events) during TS2. For each replicate tub leachate and runoff were collected in a clean 18.9 L bucket. Upon attaining complete drainage of the leachate and runoff, the volumes of the collected leachate samples were measured in lab-grade plastic graduated cylinders and transferred into clean, acid-washed 1L HDPE sample bottles.

Analysis of Water Quality Parameters

Tub study water samples (leachate and runoff) were analyzed in the University of Maryland Environmental Engineering Laboratories. Samples were measured for pH and Electrical Conductivity (EC) within a few hours of collection. Following this, 200 mL of sample was filtered through a 0.22-µm membrane for dissolved nutrient analysis. An aliquot of 100–300 mL of the sample, depending on the turbidity, was filtered for total suspended solids (TSS) (Standard Method 2540D). For nutrient (N and P) analysis, unfiltered (total organic carbon, TOC; total nitrogen, TN; total phosphorus, TP) and filtered (for nitrate, NO_3-N; ammonium, NH_4-N; total dissolved phosphorus, TDP and orthophosphate, PO_4-P) samples were stored at 4 °C without any acidification as the species were measured within 72 hours of sample collection. Total Organic Nitrogen (TON) was calculated using Eqn. 1, assuming that the nitrite (NO_2-N) fraction was negligible (<0.01 mg-N/L detection limit) in the water samples that were not analyzed for NO_2-N. Particulate (PP) and dissolved organic phosphorus (DOP) species were calculated using the mass balance Eqns 2 and 3. Table 6-1 indicates the test method and instrument information of the analyzed water quality parameters.

$$\mathrm{TN} = \mathrm{NH_4\text{-}N} + \mathrm{NO_3\text{-}N} + \mathrm{NO_2\text{-}N} + \mathrm{TON} \quad (1)$$

$$\mathrm{TP} = \mathrm{TDP} + \mathrm{PP} \quad (2)$$

$$\mathrm{TDP} = \mathrm{PO_4\text{-}P} + \mathrm{DOP} \quad (3)$$

Analysis of Soil Chemical, Physical and Geotechnical Properties

Soil Chemical Procedures

All soil samples (pre- and post- vegetative growth) used in the tub studies were tested for the parameters listed in the Table 6-2. Prior to any chemical analysis, soils were oven-dried at 55℃ for 72 hours and screened through a 2-mm opening sieve. Table 6-2 shows soil analyses and related test method information, and Table 6-3 shows the chemical properties of the soils.

Soil Physical Characterization

Particle Size Distribution: Soil samples (500 g) were initially wet sieved through a 75 µm (#200) sieve. The retained soil and the fines were oven-dried at 55 °C for 72 hours. Soil particles >75µm were then subjected to dry sieving as described in standard method AASHTO T 88 for particle size distribution. The oven-dried fines (<75 µm) were analyzed using a SALD-2300 laser diffraction particle size analyzer (PSA). The particle size distribution curves were developed using the sieve analysis and PSA data in order to classify the soils per USDA soil classification system (Fig. 6-2, Table 6-4).

Compaction Analysis: Compaction tests were performed using the Standard Proctor Test method (ASTM D698). Calculated dry densities and corresponding moisture contents were plotted, and a curve was fitted passing through these data points to determine the optimum moisture contents (w_{opt}) and the maximum dry densities ($\rho_{d,\ max}$) of the TS soils (Table 6-5).

Direct Shear Tests: Shear tests were performed per guidelines listed in ASTM 3080. A DigiShear^{TM} Automated Direct Shear System with GeoJac load actuators was used to consolidate and shear samples under specified loading conditions. Prior to sample preparation, the oven-dried soils were screened through a 4.75-mm opening sieve to avoid any interference of larger particles with shear readings. The soil specimens were compacted at optimum water content (w_{opt}) and slightly wetter ($w_{opt+3\%}$) conditions to fit into a shear box of 2.54 cm height and 6.35 cm diameter.

Three normal loads were chosen for each specimen: 15 kPa (low), 50 kPa (moderate) and 100 kPa (high). Under these loading conditions, each specimen was consolidated for 24 hours until the criteria were met per ASTM D2435 and sheared at a displacement rate of 0.5 mm/min. Shear strength parameters cohesion (c') and friction angle (ϕ') were calculated from the shear stress vs normal stress plots.

Saturated Hydraulic Conductivity Tests:

Falling head tests were conducted in flexible-wall permeameters (GEOTAC, TX) using the ASTM D5084 test procedure. The specimens (102 mm diameter and 116 mm height) were prepared at their w_{opt} in standard Proctor molds and transferred into the flexible-wall permeameters without disturbing the compaction conditions. The samples were first saturated for 7–14 days and upon meeting the saturation criteria of B>0.95 as given in ASTM D5084, the samples were then consolidated under an effective stress of 20 kPa for at least 48 hours, prior to taking conductivity readings. The test was terminated upon achieving the criterion of 4 or more determinations, to fall within ±25% of a steady-state hydraulic conductivity reading.

Constant head hydraulic conductivity tests using a GEOTAC bubble tube permeameter were conducted to determine saturated hydraulic conductivities (K_{sat}) at tub soil bulk densities (ρ_d) to mimic tub-soil compaction conditions. Soil cores from the tubs were collected using 76.2 mm diameter Shelby tubes after the growth study was completed to estimate soil ρ_d in the tubs. At these tub-soil densities, test specimens (76.2 mm diameter and 76.2 mm height) were prepared in the soil test section of the apparatus. The soil specimen sits on a perforated steel plate which was double-layered with a #100 mesh and the fabric (geotextile) that was used in the tubs, to retain the soil. The experiment was maintained at a constant hydraulic gradient of 0.9 across all soil samples. Once the sample was saturated, the Mariotte bottle was filled to a desired mark, the hydraulic conductivity readings were taken, and the criterion employed for the falling head tests was used to terminate the tests.

Data Analysis and Statistics

Depending on the data groups in the study, different statistical tests were selected to reveal correlations among parameters. When comparing nutrient mass transport in the leachate among different topsoil blends, a one-way analysis of variance (ANOVA) was completed for statistical significances. Pairwise differences among the four treatment groups were calculated using post-hoc tests with a Bonferroni correction ($P \leq \alpha$; $\alpha = 0.05/6 = 0.008$) if the ANOVA results showed significant variability. A regression analysis for correlations between leachate and soil parameters was carried out at $\alpha = 0.05$ to calculate the probabilistic significance (P) value. When an exponential correlation between parameters was noted, the P-value was determined by log transforming the dependent variable data and adding a linear fit to log(y) vs x plots.

Results and Discussion

Soil Geotechnical Properties

Direct Shear

Results of the direct shear experiments are presented in Table 2-1. With the addition of organic amendments, the effective cohesion (c’) of the soils slightly improved compared to the control soil (CUT2), following the order of BAT2 > MAT2 > LAT2 > CUT2. On the contrary, the effective friction angle (ϕ’) of the amended treatments was lower than CUT2 and stayed in a range of 32.5°–40.4°. Similarly, CUT2 has an effective cohesion of 4.1 kPa and compost amendment caused an increase of 3.5 to 7 kPa. Since the blends were non-plastic (i.e., lacking clay particles), it is speculated that the observed increase in cohesion is not true cohesion and may be due to a pore filling mechanism caused by the fine particles in topsoil.

A recent study (Duzgun et al. 2021) that tested shear properties of topsoils showed an increase in both Mohr-Coulomb shear parameters, friction angle and cohesion, with compost addition. Although this trend conforms with the c’ results of this study, it deviated from that of the friction angle (ϕ’). The difference in the application rates of amendments, compost type, and base soil properties between the two research studies could have contributed to this change in trend. Additionally, an absence of fibrous elements in the amended soils could have impacted the friction angle. Per TS1, although the soils are distinct in their properties, the effective cohesion was higher for the amended soils compared to CUT1, and vice-versa with respect to the friction angles. Since cohesion had a smaller range among the unamended and amended soils, it is unlikely that the stability of the slope would be significantly influenced by the addition of OAs under current additive rates.

Table 2-1. Shear properties of the tub study soils (TS1 and TS2)

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

As can be observed in the Mohr-Coulomb shear parameters (Table 2-1), treatments under $w_{opt+3\%}$ showed a decline in the c’ values compared to those compacted at w_{opt}. This difference in c’ was highest in BAT2 (6.9 kPa), followed by LAT1 (5.5 kPa), and the least was MAT1 and CUT2 (0.69 kPa). Similarly, wetter compactions decreased the friction angles across all the treatments, with an exception for BAT2 (ϕ’ at $w_{opt} = 32.5°$ and ϕ’ at $w_{opt+3\%} = 32.8°$). This occurs because as the water content increases, the cohesive forces between the soil particles decrease as the moisture occupies the void spaces in the soil matrix. All in all, the cohesion values (4.1-11 kPa) and friction angles (32.5-38.5°) of TS1 and TS2 soils align with those of non-plastic silty/sandy soils (9.5-14 kPa, and 31-35°, respectively) and not plastic clays (c’>15 kPa and □’<30°) (Holtz et al. 2011). Earlier work conducted on soils amended with compost (biosolids and dairy manure) showed the presence of organic matter (at <30% addition) increased the shrinkage resistance and shear strength of expansive clays (Puppala et al. 2007). Donn et al. (2014) showed that the impact of green compost on shear parameters (cohesion and friction angle) was minimal ($p > 0.05$) at the applied rates; however, a reinforced root system as a result of vegetation growth over time increased the peak shear stress in soils. From a strength perspective, it can be concluded that addition of organic amendments will improve the soil structure and can be recommended for use on highway slopes, even though the contribution of OM to shear parameters will vary depending on the amount, characteristics, and sources (Duzgun et al. 2021).

Saturated Hydraulic Conductivity

Table 2-2 provides information on saturated hydraulic conductivities (K_{sat}) of the soils at their maximum dry densities and tub bulk densities. Of the TS1 soils, MAT1 has the highest hydraulic conductivity of 5.1×10^{-6} cm/s (by one to two orders of magnitude), followed by BAT1 > LAT1 > CUT1. K_{sat} of the TS2 soils varied within the range of $1.2–7.5 \times 10^{-7}$ cm/s, again with MAT2 exhibiting the highest value. Organic amendments increased the K_{sat} of the CUT2 soil by 4.7 times in MAT2 and 3.4 times in LAT2. However, K_{sat} of CUT2 was slightly higher (1.35 times) than the K_{sat} of BAT2.

Table 2-2. Saturated hydraulic conductivities of the tub study soils (TS1 and TS2)

Tub Study Soil	***K_{sat} (at $\rho_{d,\ max}$) (cm/s)***	***K_{sat} (at ρ_{tub}) (cm/s)***
CUT1	$8.0\text{x}10^{-8}$	$2.4\text{x}10^{-3}$
MAT1	$5.1\text{x}10^{-6}$	$8.9\text{x}10^{-3}$
LAT1	$2.4\text{x}10^{-7}$	$1.6\text{x}10^{-3}$
BAT1	$2.9\text{x}10^{-7}$	$6.5\text{x}10^{-3}$
CUT2	$1.6\text{x}10^{-7}$	$1.8\text{x}10^{-3}$
MAT2	$7.5\text{x}10^{-7}$	$3.6\text{x}10^{-3}$
LAT2	$5.4\text{x}10^{-7}$	$2.5\text{x}10^{-3}$
BAT2	$1.2\text{x}10^{-7}$	$2.1\text{x}10^{-3}$

A difference of 3–5 orders of magnitude of K_{sat} was noted between the soils compacted at their maximum dry density ($\rho_{d,\ max}$) and at tub bulk density (ρ_{tub}). This can be expected given the loose packing of soils, allowing a freer movement of water through the soil matrix even under saturated conditions. A decrease in hydraulic conductivity and infiltration rates of topsoils due to compaction associated with road construction has been reported in earlier studies (Bochet and García-Fayos 2004; Haynes et al. 2013). Among the TS1 soils, LAT1 exhibits the lowest K_{sat} due to the highest fines content compared to others. Mulch application is known to contribute to increased soil pores (Onwuka and Uzoma 2018), therefore MAT1 and MAT2 outperformed other soils in their respective study sets. In general, addition of compost or compost-like materials increase soil void ratio as a result of the "fluff" phenomena (Layman et al. 2010; Kranz et al. 2020). These observations are in line with the results of other studies, where compost additions enhanced the saturated hydraulic conductivity (Bhatt and Khera 2006; Olson et al. 2013a; Cannavo et al. 2014; Duzgun et al. 2021).

Tub Studies Analysis

Vegetative Establishment and Growth

The findings and mechanisms related to the growth of a MD-SDOT standardized turf mix in the two studies are detailed in Morash (2024). To briefly summarize these results, mean vegetation (green) coverage after 6 weeks of growth was LAT1 (70±15.6%); LAT2 (96.9±0.8%); BAT1 (71.6±7.4%); BAT2 (94.9±2.3%); CUT1 (35.3±5.6%); CUT2 (90.7±1.8%); MAT1 (40.9±5.4%); and MAT2 (32.8±1.3%). The presence of biosolids and leaf compost in soils generally improved plant development, while incorporating mulch impeded turf establishment. The availability of macro- and micro-nutrients satisfied plant growth requirements in LATs and BATs, but several deficiencies were highlighted in plants in MAT soils.

Runoff and Leachate Volume

All four treatments produced leachate from each of the eight simulated rain events (SRE) in TS1. Additionally, LAT1s discharged surface runoff during some weeks, but not from all replicates. The LAT1 soil took longer to saturate and had the lowest K_{sat} under tub bulk density given its higher fines content (Fig. 6-2), compared to other TS1 treatments. The cumulative average volume of water discharged from the tubs via runoff and leachate was 64.6±5.4%, 66.8±5.7%, 57.2±2.1% and 70.8±3.1% from CUT1, MAT1, LAT1 and BAT1, respectively, with LAT1 and BAT1 being the only ones that showed any statistically significant differences ($p < 0.008$).

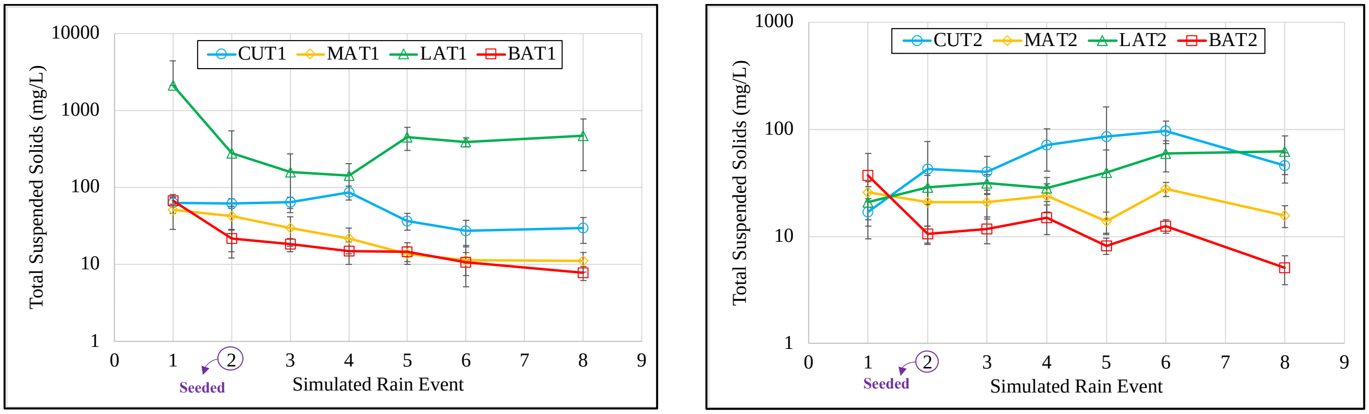
TS2 had 9 SREs during the study. CUT2 and LAT2 treatments produced runoff in the later SREs (7, 8, 9), but not in measurable quantities (<20 mL). Amendments promoted infiltration compared to the control (CUT2) soil. The cumulative infiltrated volume collected from MAT2 was the highest at 55.1±5.4% of the influent followed by BAT2 (50.9±1.2%), CUT2 (48.5±3.5%), and LAT2 (46.9±4.4%). The quantity of cumulative leachate exiting the tubs from SREs 1 to 9 was not significantly different ($p > 0.05$) across treatments and their replicates. Since the tubs were constructed on an incline of 4% (25:1 engineering slope), the slope was not steep enough to discharge significant surface runoff from the SREs in these tub experiments.

Water Quality

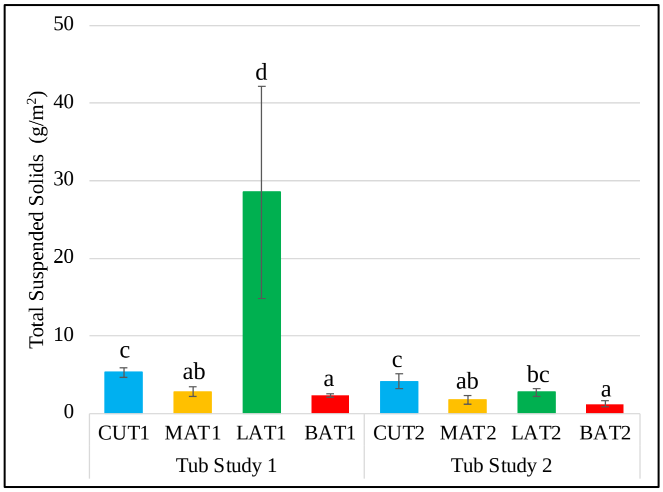
Water quality analyses were conducted on all leachate and runoff samples from SREs 1 to 8, except for SRE 7 during TS1. Therefore, TP and TN concentrations in SRE 7 leachates were estimated by taking the mean of the concentrations quantified from SREs 6 and 8 leachates. In TS2, 9 SREs were applied, of which the TP and TN were measured for all events, and the remainder of the water quality parameters were analyzed for all except SRE 7 and 9. Sediment/nutrient mass transport (g or mg/m^2) from each replicate was calculated by multiplying the concentration by the collected volume and normalizing with the tub area. Cumulative Mass Transport (CMT) was calculated by summing the individual mass transported for each replicate across the total applied in the simulated rain events.

Sediment Transport

Among the TS1 soils, LAT1 lost more sediment to leachate compared to others, with BAT1 having the least. Total suspended solids (TSS) concentrations of treatments followed CUT1, MAT1, and BAT1 showed a decline from 63.5±17.4 to 29.8±10.9 mg/L, 51.3±22.6 to 11.2±3.1 mg/L, and 67.1±6 to 7.8±1.6 mg/L, respectively (Fig. 2-1a), with successive SREs. The highest recorded mean concentration for LAT1 was 2116±2322 mg/L TSS (SRE 1) and the lowest was 143.8±59.8 mg/L TSS (SRE 4). The large standard deviation in the LAT1 soil resulted from a high TSS leaching from only one of its four replicates that skewed the data, where mean was at least 1.5 times greater than median, especially in the first two SREs.



(a) TSS (mg/L) from TS1 soils **(b)** TSS (mg/L) from TS2 soils



(c) Average of CMT (g/m^2) of TSS from TS1 and TS2 soils

Note: soils with the same letters are not significantly difference at a 95% confidence level ($\alpha = 0.05$) within their respective tub studies

Fig. 2-1. Mean concentrations (**a** and **b**) TSS from treatments used in Tub Study 1 (TS1) and Tub Study 2 (TS2), and (**c**) Average of CMT of sediment from TS1 and TS2 soils.

Since TS2 soils contained the same base soil (CUT2), specific treatment impacts on the water quality can be discerned. No common trend was seen in the TSS concentrations within the TS2 soils as time progressed. MAT2 and BAT2 followed a declining pattern of TSS leaching, while CUT2 and LAT2 showed the converse (Fig. 2-1b). The addition of mulch and biosolids to the TS2 control (CUT2) led to statistically lower CMT through leachate at 1.79±0.52 g/m^2 ($p <$

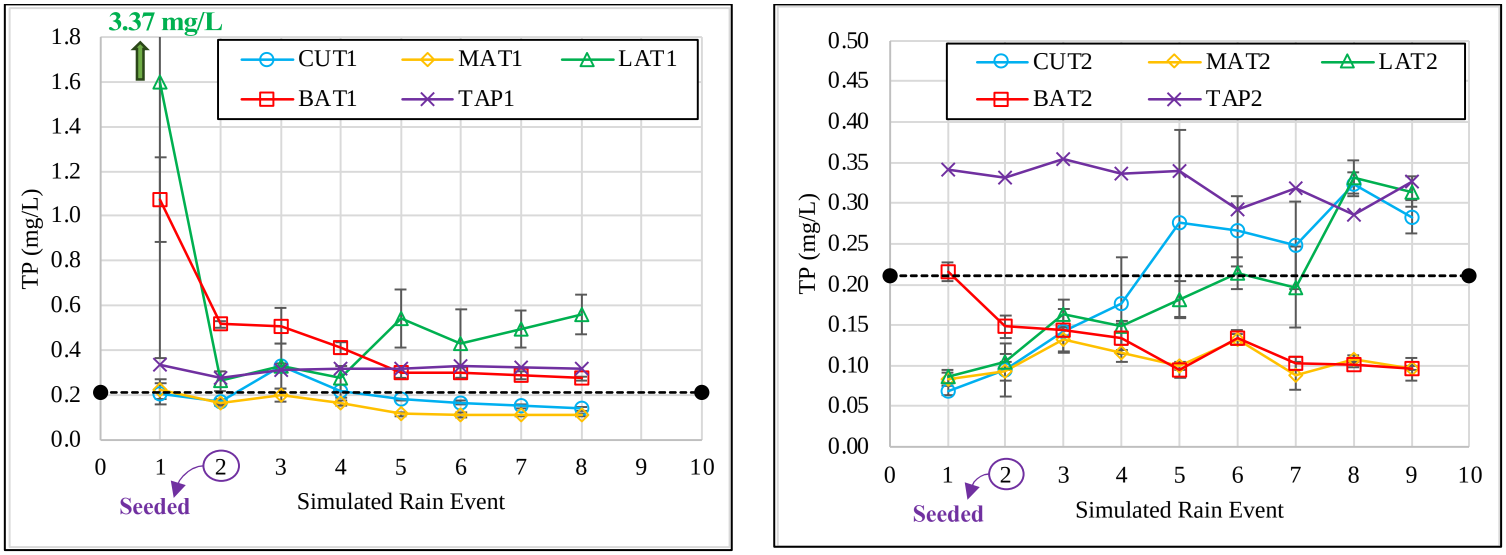
0.008) and 1.27±0.35 g/m^2 ($p < 0.008$) from MAT2 and BAT2, respectively (Fig. 2-1). LAT2 exported lower CMT compared to CUT2, however it was not significant ($p > 0.008$). Given the complexity of sediment transport through soils, estimating TSS concentrations for the excluded SREs (#7 in TS1, #7 and #9 in TS2) for each treatment could not be done, and so the calculated CMT values (in Fig. 2-1c) should be regarded as underestimates for total sediment mass loss.

Phosphorus losses

P (predominantly as PO_4-P) was present in the applied tap water (influent) at a mean concentration of ~0.3 mg-P/L. The concentration profile for TS1 soils suggests that the TP release was higher in LAT1 and BAT1 treatments when compared to CUT1 and MAT1 (Fig. 2-2a). As time progressed, the TP concentrations slowly decreased and plateaued for CUT1, MAT1 and BAT1 treatments (Fig. 2-2a). Additionally, CUT1 and MAT1 treatments were shown to reduce the tap water P levels throughout the study period. The LAT1 treatments followed a different trend with a decrease in TP until SRE 4 and a gradual increase after that to a concentration of 0.56±0.09 mg/L (greater than influent TP) during the final SRE.

TS2 allowed the determination of effects on soil due to specific amendments. Influent TP concentrations were higher than the TS2 leachates across all the rain events, except for SRE 8, where average TP concentrations in the LAT2 and CUT2 effluents were only 1.16 and 1.13 times higher than the influent. CUT2, MAT2 and LAT2 leached statistically identical ($p > 0.008$) TP concentrations (0.069±0.01 to 0.087±0.01 mg/L) during SRE 1, while BAT2 leached 0.215±0.01 mg/L, statistically greater ($p < 0.008$) than others (Fig. 2-2b). However, BAT2's removal capability of P was demonstrated in the subsequent SREs, where steady state mean effluent concentrations reduced to ~0.1 mg/L. A sustained removal (independent of the SRE) of influent TP was noted in MAT2. CUT2 and LAT2 treatments, starting with apparent adsorption of influent

P, but later TP leachate concentrations escalated to 0.28±0.02 mg/L and 0.31±0.18 mg/L respectively (which are close to the influent TP = 0.33 mg/L) in the last SRE. Cumulatively, from SREs 1 through 9, more TP mass was leached from the CUT2 treatments (20.5±2.5 mg/m^2), immediately followed by LAT2 (17.9±2.1 mg/m^2), BAT2 (13.7±0.6 mg/m^2), and finally the lowest occurring in MAT2s (11.5±1.3 mg/m^2).



(a) Average TP Concentrations (TS1) **(b)** Average TP Concentrations (TS2)

Fig. 2-2. Average concentrations of TP from treatments used in Tub Study 1 (**a**) and Tub Study 2 (**b**). Dashed line indicates typical urban stormwater mean concentration of TP = 0.21 mg-P/L (Pamuru et al. 2022). *Note: The y-axis scales are kept different between TS1 and TS2 to enhance visualization of trends.*

Phosphorus Speciation: A complete speciation of P was determined for the leachate samples collected from the treatments to better understand the details of nutrient transport in the amended soils. P appeared as dissolved (readily-available) P (PO_4-P), DOP, and PP in the TS leachates (Fig. 2-3). Across the TS1 treatments, the highest average PP was recorded in the LAT1 treatment (0.96±0.94 mg-P/L) after the first rainfall. The high standard error showed that the LAT1 replicates performed differently within the group, with one replicate leaching PP at 0.29 mg-P/L while another leached 2.35 mg-P/L. Similarly, TSS concentrations for LAT1 ranged from a low of 497 to a high of 5550 mg-TSS/L for the corresponding replicates, highlighting the association of P with soil particles in the LAT1 leachates. After the first flush of sediment in the LAT1 treatments during SRE 1, the fraction of PP was significantly reduced and leached in the range of 0.03-0.12 mg-P/L in the subsequent rain events. The strongest correlation noted between average PP and average TSS concentrations in the leachate across the eight SREs was for LAT1 ($R^2 = 0.96$, $p < 0.0001$) followed by MAT1 ($R^2 = 0.78$, $p < 0.01$) and BAT1 ($R^2 = 0.70$, $p < 0.05$). TS2 soil treatments indicated that a considerable fraction of PP contributed to the total leachable P in the water samples. PP was as high as 42.7%, 41.5%, 37.8% and 33.4% of TP (noted after SRE 3) for CUT2, MAT2, LAT2 and BAT2, respectively, across the study. However, the correlation between TSS and PP was not statistically signficant ($p > 0.05$) in the TS2 leachates, which can possibly be explained by the relatively lower concentrations of sediment discharging from the TS2 amended soils compared to their TS1 counterparts (Fig. 2-1).

The majority of the DOP was leached from the soils during the initial SREs (first flush); as the turf cover grew (Morash 2024) and as the soils continued to receive approximately 0.3 mg-P/L of PO_4-P influent with each SRE, PO_4-P became the dominant form in the leachates (Fig. 2-3). The temporal trends of DOP (descending) and PO_4-P (ascending) species in TS2 soils corroboarated with that of TS1 (Fig. 2-3), and also agreed with a recent study that tested compost/biosolids amended bioretention media (Owen et al. 2023). Although the BAT2 DOP fraction reduced with time, the final average concentration still was 0.038 mg-P/L (37.5% of TP), reduced from 0.13 mg-P/L (58% of TP, SRE 1), while CUT2, MAT2 and LAT2 declined from 60 to 7%, 40 to 0%, 63 to 2%, respectively, between SREs 1 and 8. This suggests that the rate of mineralization of the organic P from the biosolids treatment is slower than leaf compost or mulch, and/or because the amount of organic P in BAT2 is greater than LAT2 or MAT2. Continued production of DOP was noted in TS1 and TS2 leachates, particularly in BATs, suggesting that DOP has the potential to be released along with PO_4-P in organic amended soils (McDowell et al. 2021). Unlike observed in some past studies (Jay et al. 2017; Owen et al. 2023), the BAT not just retained “leachable” or dissolved soil P but also reduced the incoming PO_4-P. These results agree with those from Alvarez-Campos and Evanylo (2019), where the PO_4-P concentrations in the leachate of biosolids-applied soil were flagged as below-detectable (<0.01 mg/L) despite an increased application of phosphorus via biosolids.

Wastewater biosolids are typically treated with iron coagulants or iron salts (in their amorphous reactive form) to chemically retain or insolubilize P and other contaminants (Elliott et al. 2002; Silveira et al. 2003; Korving et al. 2019). Of all the treatments, BATs contained the highest Fe content (BAT1 = 850 mg-Fe/kg; BAT2 = 577 mg-Fe/kg), and the soils were slightly more acidic (BAT1 pH = 6.19; BAT2 pH = 6.79) among their respective treatments (Table 6-3). Therefore, PO_4-P could be stabilized by binding to the active surfaces of the iron minerals, thereby reducing the P release into the effluent beyond the first-flush of DOP from the biosolids treatment. Wood mulch soils (MAT1 and MAT2) retained the incoming PO_4-P throughout the course of the experiments. An effective removal of phosphorus by woodchips was also noted in other experimental studies (Xuan et al. 2010; Dougherty 2018; Sanchez Bustamante-Bailon et al. 2022). Sanchez Bustamante-Bailon et al. (2022) conducted batch tests and ascribed the removal of PO_4-P to the existence of Ca, Mg, Fe and Al elements in wood chips. In TS2, MAT2 contained greater Ca, Mg, Al and Fe than CUT2, and a soil P deficiency (Table 6-3, TS2). MAT2 also had a slightly alkaline soil pH of 7.31, which suggests that calcium-induced precipitation of PO_4-P in MAT2 is the primary method for reducing this nutrient’s export via infiltrated waters (Penn and Camberato 2019b).

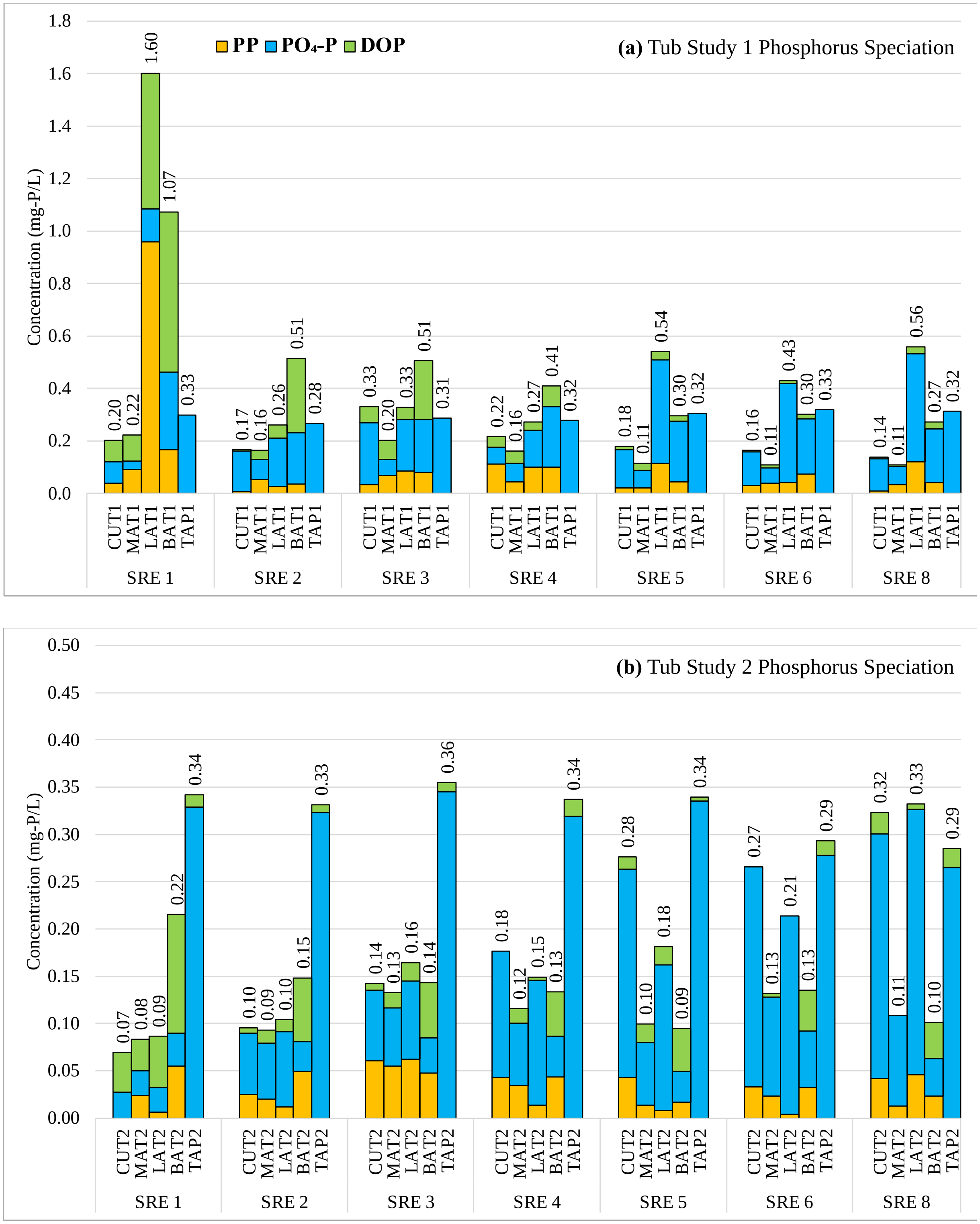


Fig. 2-3. Average concentrations of phosphorus species Tub Study 1 **(a)** and Tub Study 2 **(b)** treatments. Values on top of the bar plots denote the respective TP concentrations. *Note: The y-axis scales are kept different between TS1 and TS2 to enhance visualization of trends.*

The PO_4-P concentrations (and fraction) from CUT2 and LAT2 leachates showed an upward trend with each SRE (Fig. 2-4Fig. ***2-3***). Although leaf compost addition increased the soil mineral (Ca, Mg, Al and Fe) content in CUT2; it also resulted in elevated soil P. Because a continuous input of PO_4-P from tap water was applied during the study period, it is difficult to discern if the increase in PO_4-P over time is associated with its minerlization to PO_4-P, due to the inability of the soil to adsorb any further PO_4-P, or both in CUT2 and LAT2. Although, it can be speculated that since the plant tissue experienced P deficiencies (less than the sufficiency range of 0.3 to 0.6 %P) in all the TS2 soils (Morash 2024), it is possible that the mulch and biosolids tied up P (reduced leaching and plant availability), and the saturation of adsorption sites in the LAT2 and CUT2 soils contributed to causing an adsorption breakthrough phenomenon of PO_4-P from the influent (as seen in Fig. 2-4).

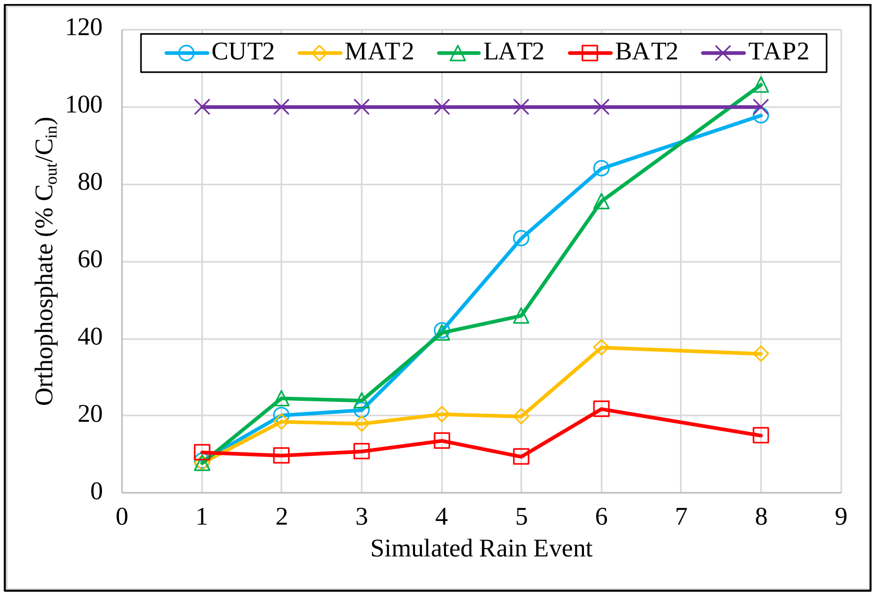


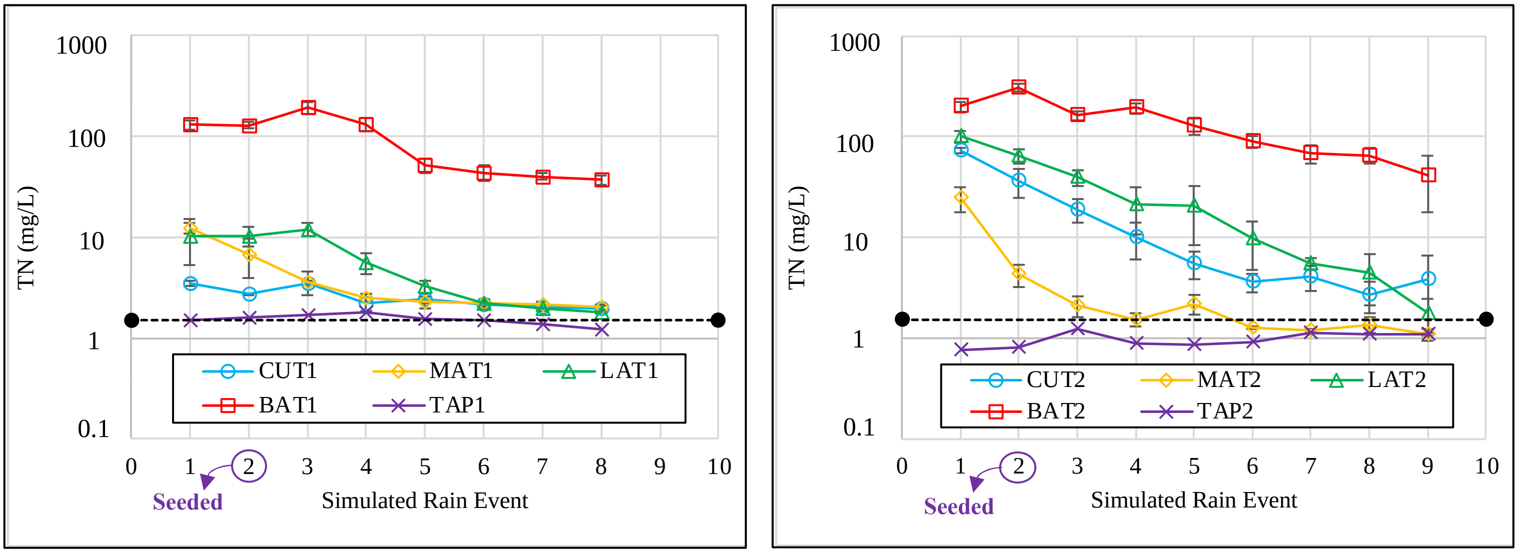
Fig. 2-4. Orthophosphate (% C_{out}/C_{in}) in the TS2 treatment leachates

P concentrations in precipitation ranged between 2-31 μg/L in New Jersey (Koelliker et al. 2004) during 1999–2001, and 16-36 μg/L near the Chasepeake Bay (collection period: 1976-1981, Boynton et al. (1995)). The influent in this study contained at least 10 times these concentrations and yet the tub study soils demonstrated an ability to retain P, indicating a potential long term adsorption of P in amended soils when the OAs are added at appropriate OM rates.

Nitrogen losses

TN concentrations in the leachate samples exceeded the incoming tap water TN levels across all treatments. CUT1 had a steady release of N (TN range: 1.96±0.12 to 3.52±0.23 mg-N/L, Fig. 2-5a) throughout the SREs, while CUT2 discharge ranged between 72.6±3.88 to 2.7±0.96 mg-N/L (Fig. 2-5b). BAT1 produced the highest release with a peak average of 191±26.1 mg-N/L during SRE 3. A decrease in BAT1 TN concentrations was observed after SRE 4 and became asymptotic at 36.6±3.8 mg-N/L after 203 mm of total simulated rainfall. Similar to TS1, the TN was the highest in the leachate from BAT2 (peak average concentration = 309±29.3 mg-N/L, SRE 2). A trending decline in TN (mg/L) leached was noted for all soils with BAT showing the sharpest downward curve (Fig. 2-5b), and the order of concentrations (in mg-N/L) after first and final SREs are: BAT2 (198±24, 41.1±23.5) > LAT2 (101±12.9, 1.8±0.7) > CUT2 (72.6±3.9, 3.9±2.8) > MAT2 (24.3±6.7, 1.1±0.1). Significantly greater nitrogen release ($p < 0.008$) was noted from biosolids (BATs) in comparison to MATs and LATs, in both TS1 and TS2 studies.

Addition of biosolids and leaf compost contributed to higher TN leaching than CUT2 in TS2 (Fig. 2-5b). This was noted in past stormwater research where amendments like leaf compost and biosolids compost exported higher N compared to the control media (Mangum et al. 2020; Owen et al. 2023). Conversely, mulch OM showed reduced N concentration (by up to an order of magnitude) compared to LAT2 and BAT2 even though the soil analysis showed that mulch increased the TN content of the control soil. TN CMT from MAT2 (464±50 mg/m^2) was the lowest compared to others (CUT2: 1577±232, LAT2: 2727±236, and BAT2: 15,142±596 mg/m^2).

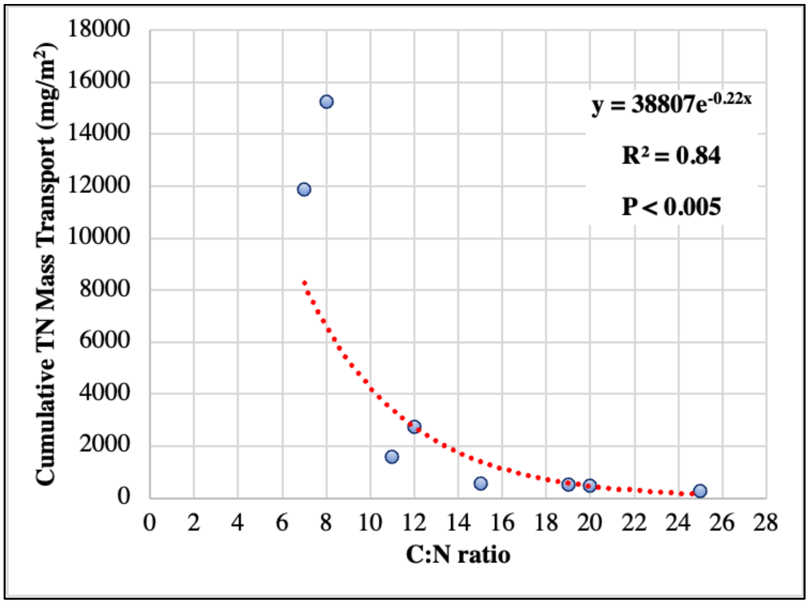


(a) Average TN Concentrations (TS1)

(b) Average TN Concentrations (TS2)

Fig. 2-5. Average concentrations of TN from treatments used in Tub Study 1 (**a**) and Tub Study 2 (**b**). Dashed line indicates typical urban stormwater concentration of TN = 1.47 mg-N/L (26% of which is NO_3-N and 13% is NH_4-N) (Pamuru et al. 2022).

Previous research has noted a negative correlation of soil C:N with TN loss from media (Dise et al. 1998; Zhou 2017; McPhillips et al. 2018). Soil C:N ratio is identified as a key soil property in determining TN leaching from the amended soils examined in this study. Fig. 2-6 shows the leachate TN CMT vs initial soil C:N ratio for all TS soils. A decreasing exponential trendline best fit the data and the computed goodness of fit (R^2) of 0.84 indicates a strong statistical correlation ($p < 0.05$). Of the eight soils, the treatments with the lowest C:N ratios (7:1, BAT1 and 8:1, BAT2), given their high N content, leached statistically more TN by mass ($p < 0.008$) compared to the others. Contrary to this, CUT1, MAT1, MAT2 had C:N ratios greater than 19:1 and leached <25 mg/L TN (Fig. 2-5). Soil microorganisms sequester N while feeding on C (cellulose in the case of mulch) to meet their N demands when the soil C:N ratio is greater than 20:1 (Chapin et al. 2002; McPhillips et al. 2018). Carbon-rich organic materials like mulch could also prompt denitrification in MATs when anaerobic microsites are created with weekly rain simulations. This denitrification process has been discussed in woodchip bioreactor studies in the context of nitrate removal (Halaburka et al. 2017; Ashoori et al. 2019; Aalto et al. 2020; Fan et al. 2022). This renders the nutrient (temporarily) unavailable for plant uptake, thus transforming it into a limiting factor for vegetative growth in these soil blends as evidenced in the N tissue uptake from the studies (Morash 2024). Therefore, from the vantage of water quality, mulch-like OAs with C:N >20:1 reduce N leaching; however, at the cost of compromised rapid vegetation establishment.



(a) TN cumulative mass transport vs initial soil C:N ratio

Fig. 2-6. Effects of soil C:N ratio on TN cumulative mass export as determined from the eight-tub study soils

Nitrogen Speciation: Tap water N was 91.5 to 100% in the form of NO_3-N. Unlike P speciation, major N forms were in the dissolved phase (Fig. 2-7). NO_3-N and TON were predominately found in all leachates, while NH_4-N appeared only in the BAT leachates.

BAT1 leached a notable fraction of NH_4-N in the first 3 SREs respectively (Fig. 2-7a). Overall, NH_4-N in BAT1 effluent dropped from an average concentration of 93±13.7 mg-N/L to 1.1±0.3 mg-N/L from the initial to final SRE. A small amount of NH_4-N (7% of TN) was found after the first SRE in BAT2 leachate, unlike BAT1 where the NH_4-N release was quantifiable throughout the course of the experiment. The same biosolid material (originally procured in May 2021) used in the BAT1 blend was stored in closed-lid buckets and reused in September 2021 to prepare BAT2. Since a more aged material was used for BAT2, it is possible that NH_4 might have mineralized to NO_3 causing a higher fractional output of NO_3 over NH_4 in the BAT2 leachates. This brief appearance of NH_4-N in both soil and aqueous environments could also occur as a result of volatilization (Lea-Cox et al. 2001), although gaseous N forms were not measured in the current study. Soil NH_4-N information was available only for TS2 soils (Table 6-3), and NH_4-N was the highest in BAT2 compared to other soils. This confirmed and reflected the existence of NH_4-N only in the BAT2 leachates.

Effluent TON fraction of BAT1 was high (11%, 36%, 48% of TN) until SRE 3. With time, as TON started to mineralize due to microbial activity and as subsequent nitrification occurred, the fraction of TON decreased, and soluble (plant available) NO_3-N became the dominant species starting with SRE 4 (Fig. 2-7a). At the end of TS1 (SRE 8), NO_3-N in leachates were below 2 mg-N/L in all soils except for BAT1 which was still leaching 24.3±1.74 mg-N/L (66% of TN) (Fig. 2-7b). Although effective for P retention, the biosolids increased the risk of NO_3-N pollution to ground- and surface water pathways, which has been highlighted in several past studies as well (Correa et al. 2006; Rigby et al. 2009; Alvarez-Campos and Evanylo 2019; Owen et al. 2023). Effluent from TS2 treatments contained greater NO_3-N concentrations, compared to TS1. This is attributed to the low C:N ratios (8:1 to 20:1) of TS2 soils compared to TS1 (7:1 to 25:1). NO_3-N remained the dominant N species leached from all the TS2 soils, with TON (albeit fractionally lower compared to NO_3-N) second through successive SREs. A transient product of nitrification, nitrite (NO_2-N) was analyzed for a few events (not shown in Fig. 2-7) and was found to be negligible (all less than 2% of TN) in the mass balance of N species for all soils.

Soil NO_3-N concentrations followed the order: BAT2>LAT2>CUT2>MAT2 (Table 6-3). This same sequence was noted in the corresponding leachates, with MAT2 exporting the least (61-92% less nitrate compared to CUT2). Similar to biosolids, leaf compost used in TS2 also contributed to excessive nitrate leaching in the initial flush but was rapidly reduced from 97.9±13.9 to 3.36±1.41 mg-N/L; a continued reduction in LAT2 N species and TN concentrations was observed, unlike other soil leachates which attained steady state (Fig. 2-5&Fig***. 2-7***). This implies that further reduction in N release could have occurred if the experiment prolonged beyond the 9 weeks of study.

According to the National Atmospheric Deposition Program (NADP) database, the annual mean rainfall nitrate concentrations in the Beltsville region of Maryland (site ID: MD99, http://nadp.slh.wisc.edu/data/NTN/) between Dec 2020 and 2021 was ~0.14 mg-N/L. This suggests that the composition and characteristics of the roadside soils are more important factors in determining nitrogen movement than the small amount of nitrogen that is introduced from rainfall in the field.

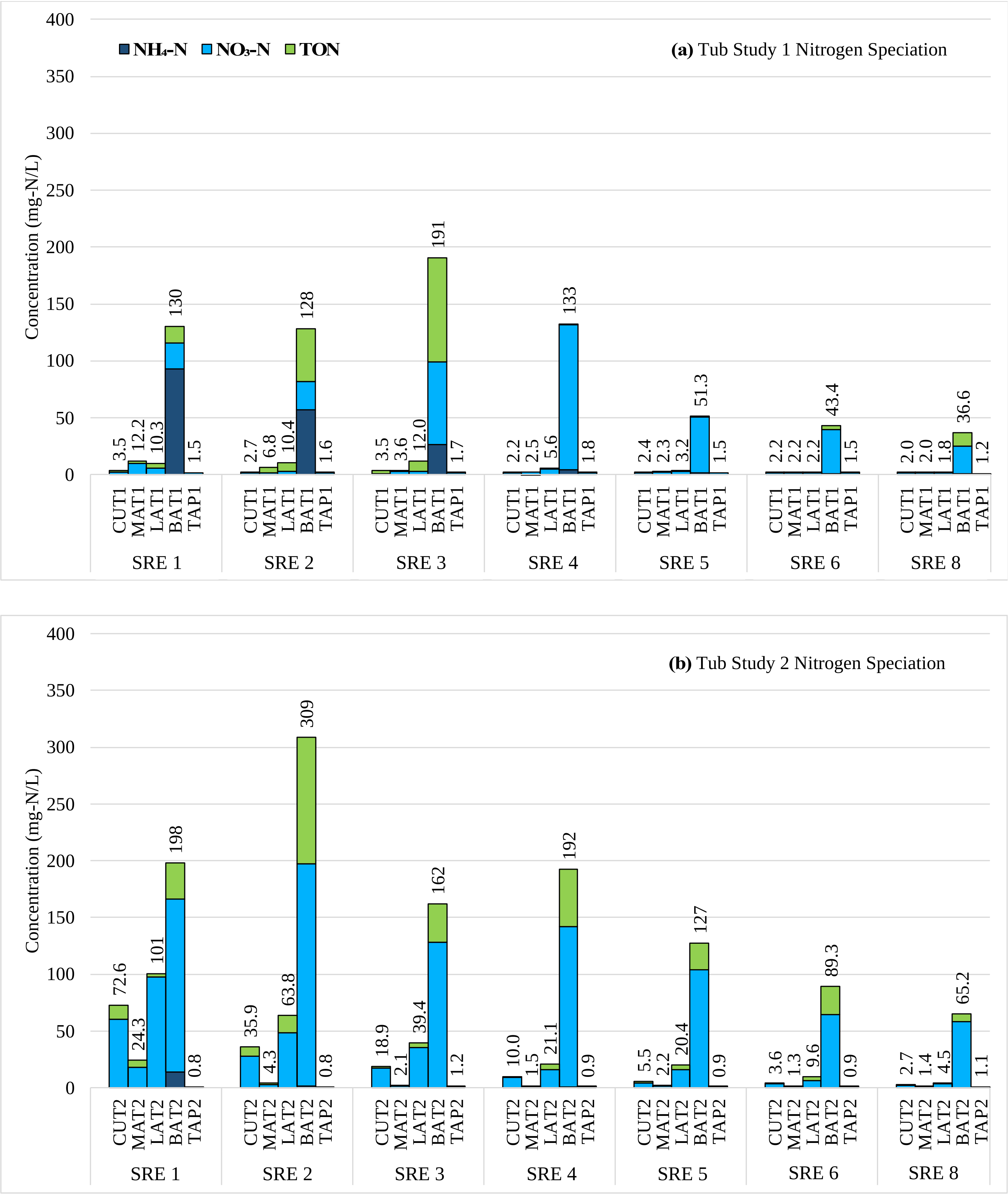


Fig. 2-7. Average concentrations of nitrogen species Tub Study 1 (a) and Tub Study 2 (b) treatments. Values on top of the bar plots denote the respective TN concentrations

Surface water discharge (LAT1)

During 4 out of the 8 SRE, LAT1 treatments produced surface runoff in addition to leachate. Table 6-6 shows TP and TN concentrations and the corresponding mass transport from these SREs. TP concentrations in surface runoff were 1-4 fold higher compared to the corresponding subsurface (leachate) release across all treatments because the P in soils is relatively stable and immobile as it binds with minerals (Lehmann and Schroth 2002; Spohn 2020). On the contrary, more P by mass was lost to subsurface water than runoff because of the differences in volume between the two discharges; leachates had 3.4 to 18.8 times more volume than runoff. TN concentrations in the leachate were greater than runoff (as expected under pre-growth conditions); however, in time, the N from both aqueous pathways ranged between 1.73–6 mg-N/L (SREs 5, 6 and 8). Similar to P, more N by mass was lost via leachate than runoff in corresponding rain events.

Using the information in the national stormwater quality and the BMP databases, the median value of stormwater TN is estimated to be 1.47 mg-N/L (N=2186) and TP to be 0.21 mg-P/L (N=7961) from across US urban land uses (Pamuru et al. 2022). The leachate effluent concentrations from the treatments exceeded the stormwater TN throughout the trial, except for MAT2, which had average steady state values (SREs 8&9) ranging between 1.09±0.14 and 1.36±0.26 mg/L (Fig. 2-5c). CUT1, MAT1, MAT2 and BAT2 (50% of the treatments) released TP at concentrations lower than 0.21 mg-P/L by the end of the respective growth studies. With LAT1 as an exception, the remaining 7 soils successfully reduced influent P levels during the experiments. This suggests that P leaching from amended soils (with OM content between 4–8%) is minimal and may not necessarily exacerbate the current stormwater P issues in events where the leachate may combine with surface runoff.

Conclusions

Three distinct organic amendments (shredded wood-mulch, leaf compost, and biosolids) were tested in two greenhouse tub studies to assess their efficacy in promoting turf coverage, improving soil physical characteristics, and preserving water quality. This research was divided into two sections, and the present paper specifically examined the influences of OAs on geotechnical and environmental properties.

Geotechnical Properties: Shear properties of all the OA-amended study soils were comparable to those of earthen materials. Compacting the soils at $w_{opt+3\%}$ reduced the overall shear strength of the soils as expected, even though differences in LAT and BAT treatments at w_{opt} and $w_{opt+3\%}$ were greater. Conclusions about how these differences could affect erosion potential could not be determined in this study. MAT soils had the highest hydraulic conductivities at $\square_{d, max}$ and $\square_{tub}$ compared to the other treatments in both tub studies, which means that mulch greatly increased saturated hydraulic conductivity of the soils.

Leaching: Water quality analysis of N species demonstrated that biosolids caused a notable increase of N export (by 1-2 orders of magnitude) when compared to other amendments. An exponential decay relationship was evident between soil C:N ratio and the TN CMT data. The soils with a combination of low C:N ratio and high TN content (BATs) released more N in the leachate. The opposite was also true, in that MATs (high C:N ratio) leached the lowest N. Although leaf compost leached N greater than typical urban stormwater concentrations (TN = 1.47 mg-N/L) at the beginning of the SREs, the concentrations dropped to 1.8 mg-N/L and 4.5 mg-N/L for LAT1 and LAT2, respectively, in the end of the experiment.

Biosolids amendment successfully reduced the influent tap water P (~0.3 mg-P/L) to levels below typical stormwater concentrations (TP = 0.21 mg-P/L) in the leachate. Irrespective of a P increase in BATs, the abundance of iron along with other background minerals (Al, Ca, Mg) in biosolids, effectively complexed P for the duration of the study. Low P content and high minerals (particularly Ca) were characteristics of the wood mulch amendment and MATs also minimized the P release into the leachate, with concentrations lower than typical stormwater levels at all points during the experiment. Although CUT2 and LAT2 removed tap water P at the initiation of SREs, the effluent concentrations did not statistically differ from the influent after 203 mm of simulated rainfall, suggesting a possible breakthrough due to oversaturation of P adsorption sites in these soils. The final distributions of P and N in the soil, leachate and plant, as influenced by the amendments are shown in Fig. 2-8 and Fig. 2-9, respectively.

Recommendations

1. Biosolids amendment should be added into roadway topsoil soils based on nitrogen requirements and not be used as a means to raise the soil OM content.
2. At inclines greater than 25:1 used in this study, lateral surface- and subsurface- flows could occur. Since the tub studies determined that biosolids significantly increased N concentrations in leachate, the risk of high runoff N concentrations could be greater at steeper inclines.
3. Due to their high C:N ratio, MATs effectively retained N in the soils. Concurrently, in terms of plant growth, the wood-mulch caused tissue N and other nutrient deficiencies (Morash 2024). Given its widespread use, it is recommended to complement mulch with fertilizers rather than relying solely on it as the primary source of OM and nutrients. This approach is essential for achieving the desired vegetation outcomes while also maintaining water quality.

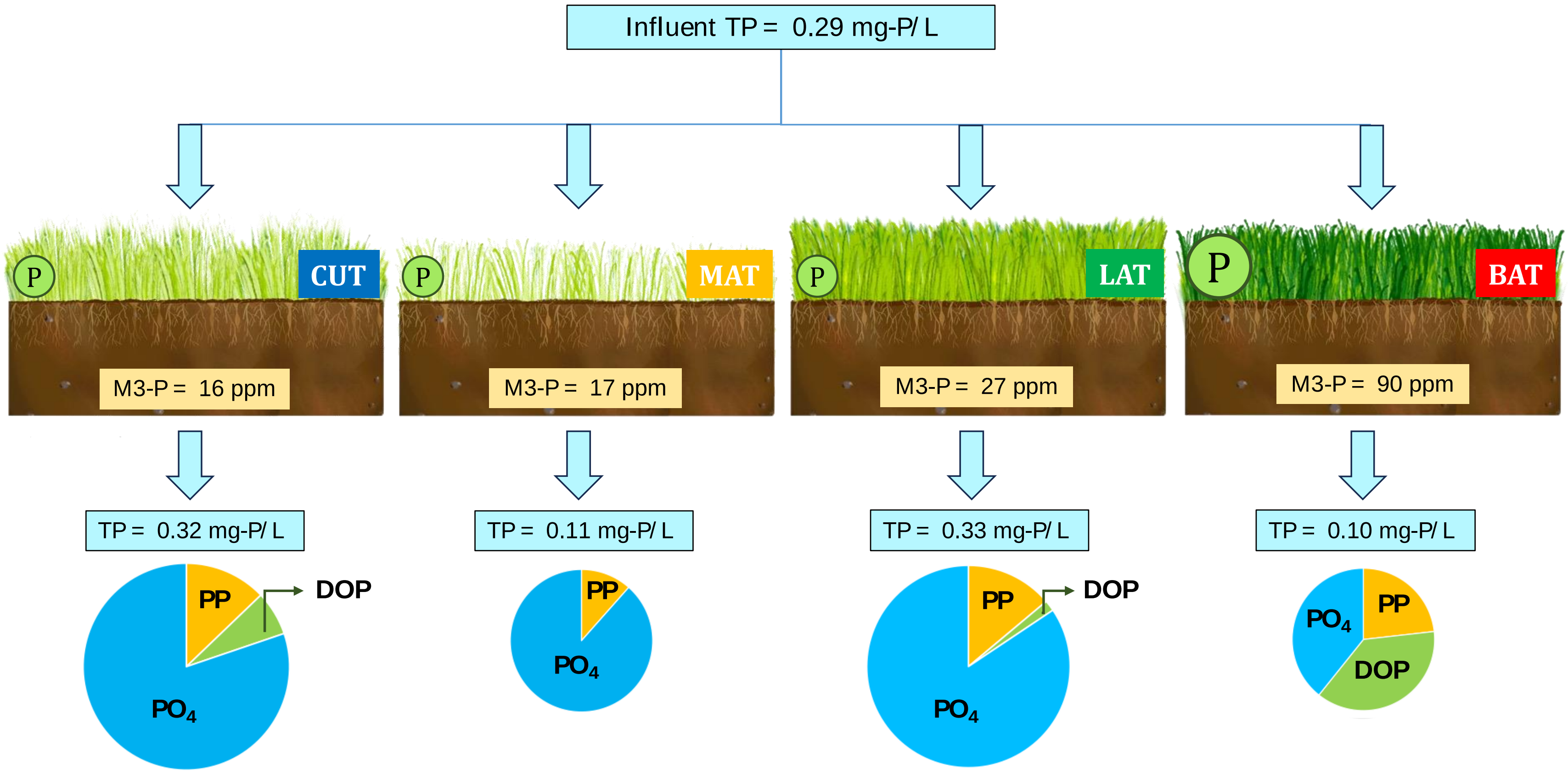


Fig. 2-8. Phosphorus distribution in the steady state leachate and uptake as affected by the addition of OAs. Information related to plant coverage, color and uptake is provided in Morash (2024)

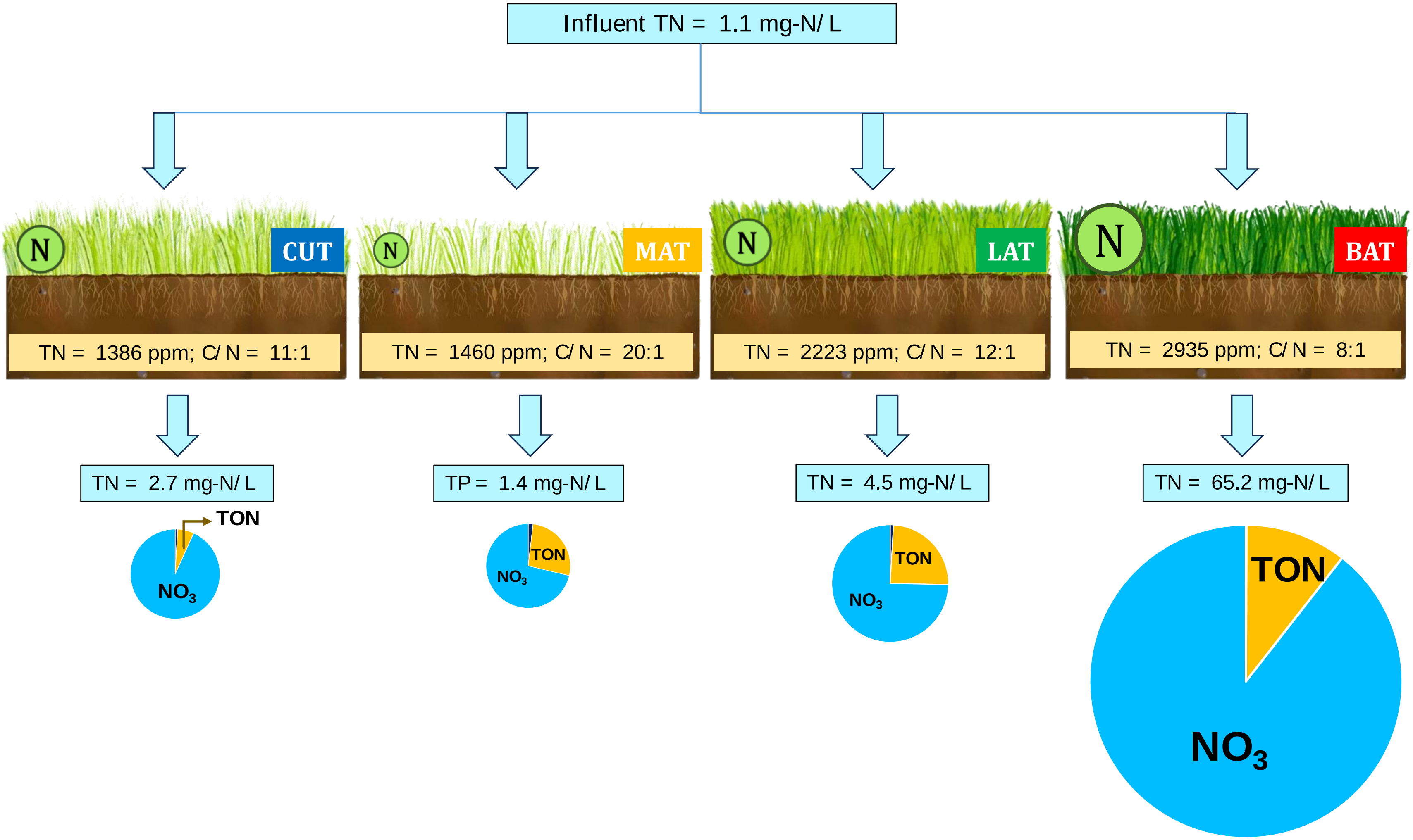


Fig. 2-9. Nitrogen distribution in the steady state leachate and uptake as affected by the addition of OAs. Information related to plant coverage, color and uptake is provided in Morash (2024)

4. N release from LAT2 continued to decline with each rainfall application, and this soil also removed P from the influent albeit following a breakthrough-like phenomenon. Therefore, leaf compost-like amendments are suggested as the preferred materials to be incorporated into soils for improving the OM content in the context of soil fertility (Morash 2024), with reduced concerns around water quality.
5. Given its potential for a reduced risk of nitrogen release and the ability to retain phosphorus, leaf compost could be a suitable choice from a water quality and nutrient availability perspective (Morash 2024), when applied at suitable soil organic matter rates (MDOT SHA 2017b).

Acknowledgements

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CHAPTER 3. OPTIMIZING NATIVE VEGETATION ESTABLISHMENT IN URBAN SOILS: ASSESSING THE IMPACTS OF ORGANIC AMENDMENTS ON SPECIFIC GROWTH PARAMETERS

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Abstract

Establishing healthy roadside vegetation offers numerous benefits, including the reduction surface water runoff, improved soil quality, reduced erosion, and an aesthetic landscape. The use of conventional vegetation establishment methods can be economically inefficient, and guidelines are not clear regarding optimum mixing ratios for compost or compost-like organic soil amendments in poor soils. This project aims to explore the use of organic soil amendments (OAs) as an alternative to conventional vegetation growth approaches. Three sandy loam soils and one clayey soil were chosen for the study. OAs included yard waste (Y), food waste (F), turkey litter and green waste-based (T) composts, and wood-derived biochar (B). The application of OAs was based on the organic matter (OM) percentage of soils. A selection of 7 native species (grasses and forbs) was used for the pot study experiment. A total of 156 pots (4 soils + 4 soils x 4 OAs x 3 application rates, prepared in triplicates) were assembled. Biweekly assessments of percent green coverage (%GC) results indicated that soluble salt content from the T amendment either delayed or curtailed plant growth in the soils. A significant correlation between the electrical conductivity (soluble salts) of soil-OA blends and corresponding %GC was found over the study period.

Notably, some soils amended with biochar exhibited rapid vegetation coverage during the initial growth stages compared to other soil-OA blends. However, Biochar reduced the plant uptake of N and leaf area of predominantly emerged black-eyed Susan (BES) plants. This suggests that the extent of plant coverage in soil-biochar blends may not necessarily reflect the overall plant health. In contrast, N uptake was higher in the BES plants emerging from composts T, F, and Y compared to Biochar. Therefore, while the biochar amendment achieved the desired vegetation coverage, composts surpassed this amendment in terms of plant health. It is recommended to minimize the use of concentrated manure-based (e.g., turkey litter) composts for roadside projects as an OM source. Alternatively, wood-based biochar needs to be enriched with nutrients when used as a soil amendment. Within the current study, composts such as F and Y were well suited to establish healthy and long-lasting vegetation.

Introduction

Vegetation is a critical component in the context of soil restoration. Its establishment effectively alleviates soil erosion and stormwater issues by (1) regulating stormwater flow and reducing runoff volume through rainfall interception, (2) shielding the exposed soil surface from high velocity rainfall, (3) achieving stormwater pollutant removal through phytoremediation, sorption, filtration, and sedimentation, and (4) reducing stormwater export through evapotranspiration (Muerdter et al. 2018; US EPA 2013a). The use of native vegetation (eg., prairie plants) in particular offers advantages over turf grasses due to their dense and deep root systems (US EPA 2015b; Bloorchian et al. 2016; Hillhouse et al. 2018). Native landscaping can thus loosen post construction compacted soils, enhance infiltration, and contributes to more effective stormwater reduction, besides promoting biodiversity.

Admixing organic amendments (OA) into soils stands out as a cost-effective soil quality conservation and restoration technique, in demonstrating potential in promoting vegetation, and deeper roots improving soil structure (Heitman and McLaughlin 2017; Kranz et al. 2020; Olson et al. 2013b; Weiss et al. 2005). OAs enhance the organic matter (OM) content of soils, which is instrumental in improving carbon sequestration and providing soil its health and nutritional quality (Flavel and Murphy 2006; Wu et al. 2021). In horticulture, compost- and manure- based organic soil conditioners have resulted in producing greater plant productivity and yield (Adugna 2018; Cheng et al. 2007; Evanylo et al. 2016). A recent greenhouse study tested two composts for turf establishment, one was a blend of yard waste, food waste, biosolids and woody materials; the other consisted of yard waste, food waste and woody materials, that were incorporated into a sandy loam soil at increasing additive rates (Kranz et al. 2021). Biomass production and plant cover was greater in the compost amended soils compared to the study controls. A similar trend was noted by Evanylo et al. (2016) where the turf biomass was the greatest at the highest compost incorporation rate into control soil. Other greenhouse and field-based research also observed a concomitant improvement in turf grass establishment due to the addition of organic composts (Garling and Boehm 2001; Linde and Hepner 2005; Kranz et al. 2021; Owen et al. 2021). Composts or related organic materials increase soil fertility, soil microbial activity, water holding capacity, and infiltration, all of which are drivers of healthy vegetation (Adugna 2018; Kranz et al. 2020). However, not all composts successfully improve plant yield. Feedstock elements of compost or organic materials display different effects on plant growth. A recent study that evaluated composts from different feedstock sources showed that nutrient-rich composts (derived from manure or food scraps) enhanced green vegetation and growth; however, compost derived from woody green waste material, due to its low nitrogen (N) content, lowered growth (Heyman et al. 2019).

Another widely studied soil conditioner is biochar, a stable carbonaceous byproduct of the pyrolysis processes, typically produced at or above 300 °C (Lehmann et al. 2011; Fidel et al. 2017; Oni et al. 2019; USDA ARS 2021). The sources of biomass used as feedstock (e.g., animal wastes, food scraps, plant debris, wood waste, etc.,) and the specific production variables (e.g., pyrolysis temperature, heating rate) greatly affect its structure and stability (Kaya et al. 2022). Biochar addition has proven to be an effective soil remediation strategy as it improves soil porosity, water retention, and, depending on its parental elements, it can also increase the fertility status of soils (Steiner et al. 2008; Agegnehu et al. 2015; Ding et al. 2016). A study by Laird et al. (2010) on mesic types of soil from Iowa showed that cation exchange capacity (up to 20%) and pH of soils increased with addition of biochar. Similar increase in CEC values due to biochar addition on high yielding croplands in Northern China was also observed by Chen et al. (2011). In the field, the addition of charcoal to a fertilized soil was observed to increase N retention in soils and improve its uptake by plant (Steiner et al. 2008). A comprehensive review that synthesized information from 634 biochar-related studies in the context of soil fertility found that, on average, the use of biochar amendment led to a crop yield increase of approximately 20% (Agegnehu et al. 2017). However, similar to observations made with composts, biochar produced from wood-derived sources can lack plant-available nutrients (N and P), which may limit vegetation growth (Agegnehu et al. 2017; Singh et al. 2010). This underscores the importance of understanding the base properties of composts and biochar to identify the right organic materials that fit the environmental goals.

Copious literature (as referenced earlier) is available, centering around establishing fast-growing turf grasses for roadside applications. However, scientific research that focuses on a mixture of native forbs (e.g., *Rudbeckia hirta* L.) and grass (e.g., *Andropogon gerardii* Vitman) species is notably sparse, particularly in the context of organic amendments. Native species typically have a longer growth period because of their inherent adaptation to thrive in environments with limited resources (Vallano et al. 2012; Shivega and Aldrich-Wolfe 2017). Therefore, this greenhouse pot study was conducted to test the efficacy of organic amendments (composts and biochar) in improving the quality of low-grade urban soils to facilitate rapid vegetation growth. In line with the benefits surrounding growing native vegetation, this study also adopted polyculture plantations to provide complementary growth coverage. The goal of this project is to delineate the distinct influences of different promising organic amendments when introduced (independently) as sources for OM into four urban roadside topsoils. Furthermore, the study aims to pinpoint the optimal soil-OA blends that satisfy the prerequisites of supplying essential nutrients for accelerated and healthy plant growth and establishing the foundation for soil restoration, by comprehensively evaluating soil properties that lead to enhanced growth. This can help in tailoring the soil amendments as needed in the field to meet the current vegetation goals.

Materials and Methods

Soil and Organic Amendments

Three sandy loam soils from Glenwood (G), Sanborn (S), and Clearwater (C) areas and one clayey soil from the Ortonville (O) region of Minnesota were chosen for the study. Soil source locations and classifications are presented in Table 6-7. Fig. 6-4 shows the grain size distributions (ASTM D 6913, ASTM D 1140, ASTM D 422), and compaction characteristics (ASTM D698) of each material. Investigated OAs include yard waste (Y), food waste (F), turkey litter and green waste-based composts, and a wood-derived biochar (B).

Table 3-1. Soil analyses, methods, instruments, and detection limits

Soil Property	Units	Method	Instrument	Detection Limit
pH	-	ASTM D4972	VWR symphony B40PCID	2
EC	µS/cm	EPA method 9050A	VWR symphony B40PCID	0.001 µS/cm
OM content (LOI at 455 °C)	%	AASHTO T267	Thermonlyne^{TM} Muffle Furnaces	
TC	%	Combustion at 950 °C (infrared detection)	LECO CN628 analyzer, LECO corporation	0.0001%
TN	%	Combustion at 950 °C (thermal conductivity)	LECO CN628 analyzer, LECO corporation	0.0001%
NO_3-N, NH_4-N	ppm	KCl extraction	SEAL AQ300 Discrete Analyzer	1 ppm
M3-P	ppm	Mehlich-3 extraction	Shimadzu Model ICPE-9820	0.1 ppm

EC: Electrical conductivity, OM: Organic matter, LOI: Loss on ignition, TC: Total carbon, TN: Total nitrogen, M3-P: Mehlich-3 Phosphorus

Soil Chemical Analysis

The following data were collected for the soils and OAs: pH, electrical conductivity (EC), organic matter content (OM% - measured as LOI at 455 °C), nitrogen species (Nitrate-N, Ammonium-N, Total N), Mehlich-3 Phosphorus, and total carbon. Prior to chemical testing, all soil samples were oven-dried at 55°C for 72 hours and screened through a 2-mm opening sieve. Table 3-1 shows the soil properties that were measured at the University of Maryland Environmental Engineering laboratories and their test-related information. Furthermore, soils and OAs were sent to the Cornell Soil Health Laboratory to analyze for predicted autoclave-citrate extractable (ACE) protein (mg extracted/g of soil) and soil respiration (mg CO_2 released/g of soil), both of which are biological soil indicators (Moebius-Clune et al. 2016). Table 3-2 presents the summary of the chemical properties of the soils and OAs, respectively.

OA Application Rates

The OAs were applied to the soils as a function of the soil OM content. The Minnesota department of transportation's (MnDOT) OM criteria for topsoil materials was chosen as the soils were procured from Minnesota. One of the criteria for topsoil is the OM content to be between 3% and 15% as listed in their *Standard Specifications for Construction* guide (MnDOT 2020, Section 3877, Test Method: ASTM D2974). Since high rate application of composts can lead to unintended consequences such as nutrient leaching, as demonstrated by previous studies (Hansen et al. 2012; Owen et al. 2021; Puppala Anand J. et al. 2011), soil blends in this study were confined to an upper bound of 10% OM. Each OA was applied to the soil at rates that correspond to a target OMs of 5%, 7.5% and 10% for three soils, with the exception of the Ortonville soil. Ortonville soil had an average OM content of 5.39% so the application rates targeted blends to reach 7.5%, 10% and 13% OM.

Table 3-2. Chemical analyses of the study soils and organic amendments (OA)

		Soils				**Organic Amendments (OAs)**			
Property	**Units**	**Clearwater**	**Glenwood**	**Ortonville**	**Sanborn**	**Biochar**	**Turkey-Litter Compost**	**Food-waste Compost**	**Yard-waste Compost**
pH		7.46±0.05	7.45±0.12	7.75±0.03	7.98±0.02	9.42±0.08	6.8±0.07	7.65±0.03	7.52±0.05
EC	µS/cm	453±10.7	335±37	313±46.4	197±3.5	801±46	15200±440	4730±236	3040±219
OM (LOI)	%	3.02±0.03	3.76±0.07	5.39±0.11	3.32±0.04	68.9±1.3	41.6±3.59	27.9±1.19	31.7±2.16
C:N*		9.5	10.2	9.5	11.5	114	9.3	12.2	13.3
C	%	1.55±0.18	2.22±0.26	2.55±0.04	2.09±0.09	76.7±1.31	24.9±0.4	20.7±0.76	18.4±0.88
N	%	0.16±0.02	0.22±0.01	0.27±0.01	0.18±0.01	0.67±0.03	2.67±0.09	1.7±0.07	1.39±0.08
NH_4:NO_3		1.03	1.6	1.34	7.62	1.65	23.9	1.22	1.23
NO_3-N	mg-N/kg	36.9±0.73	21.2±1.19	42.4±0.54	6.1±0.11	4.32±1.26	29.6±2.56	40.4±18.2	38±12.4
NH_4-N	mg-N/kg	38±0.6	33.9±0.71	57±4.36	46.5±1.76	7.14±3.68	706±74.4	49.2±3.5	46.8±3.09
Extractable P‡	mg-P/kg	5.2	1.7	4.9	6.5	599	4841	650	573
ACE Soil Protein‡	mg/g	4.7	4.6	5.3	4.4	0.3	85	63.3	33.6
Soil Respiration‡	mg/g	0.4	0.5	0.4	0.6	0.7	2.3	2.6	2

All values are denoted as **Mean±SD** of three representative samples. *C:N and NH_4:NO_3 ratios are calculated using the means of C%, N% and NH_4, NO_3, respectively, hence SD is not included ‡Measurements for extractable P (Modified Morgan soil test method) and biological indicators obtained from Cornell Soil Health Laboratory (Fig. 6-16 and Fig. 6-17).

Seed-mix

A seed mix that comprised of graminoids (grasses) and forb (flowers) species common to MnDOT native seed mixes was selected for this study. The seed mix encompasses three types of seeds: grain size seeds (slender wheatgrass), fluffy seeds (big bluestem, Kalm's brome), and small or fine seeds (black-eyed Susan, Canada milk vetch, purple prairie clover, and Indian grass). Information pertaining to the plant species of the seed mix, their individual seasonal preferences (warm vs cool) and application rates is given in Table 3-3.

Table 3-3. Composition of species included in the seed-mix

Seed Name	**Scientific Name**	**Season**	**Percent in Mixture (%)**	**Seeding Rate (g/m^2)**
Big Bluestem (Native)	*Andropogon gerardii* Vitman	Warm	20	0.79
Indian Grass (Native)	*Sorghastrum nutans* (L.) Nash	Warm	20	0.79
Slender Wheatgrass (Native)	*Elymus trachycaulus* (Link) Gould ex Shinners	Cool	30	1.23
Kalm's Brome (Native)	*Bromus kalmia* Gray	Cool	20	0.79
Black-Eyed Susan (Native)	*Rudbeckia hirta* L.	Cool to Warm	5	0.22
Purple Prairie Clover	*Dalea purpurea* Vent.	Warm	3	0.11
Canada Milk Vetch	*Astragalus canadensis* L.	Warm	2	0.11
Total			***100***	***4.04***

Pot Experiment

Pot Definition

A total of 156 (25.4-cm in diameter) pots (4 controls + 4 soils x 4 OAs x 3 OA rates, prepared in triplicates) were assembled in the UMD research greenhouse complex. Each pot contained two layers of a 5.1 cm subsoil (or compacted) layer at the bottom and a 10.2 cm fertile layer on the top (Fig. 3-1). The subsoil layer was the respective soil without any amendments, compacted to its maximum dry density. This was done to ensure that the seeds and the soil were contained within the pot, attempting to mimic field conditions. The fertile layer consisted of the soil amendment blends responsible for vegetation establishment.

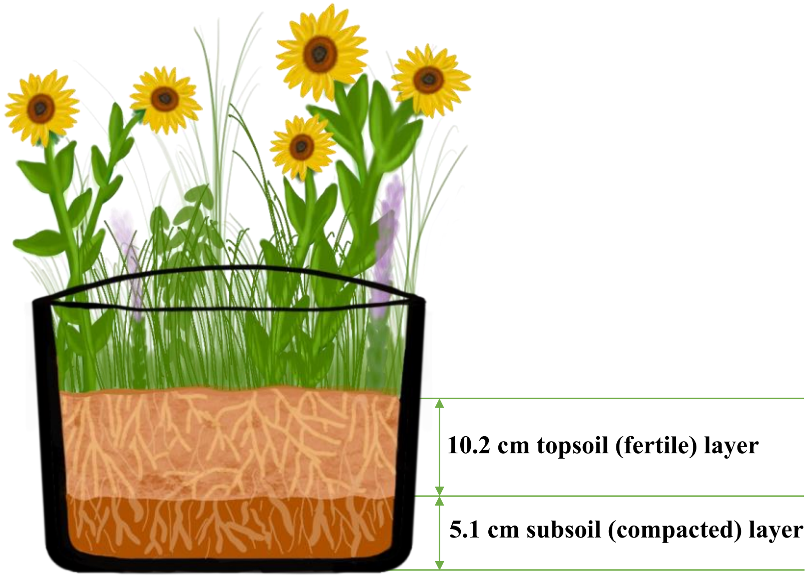


Fig. 3-1. Schematic representation of a pot with soil layers

Pot Preparation

Plant debris (roots) and rocks (>2.54 cm) were separated from the soils to the extent feasible before placing the soils in the pot. Subsoil was placed and compacted into the pot at an amount that corresponds for a 5.1 cm depth to its maximum dry density. Maximum dry density of soils (Table 6-8) was determined by following the standard proctor procedure (ASTM D698). The second layer is topsoil (fertile layer), 10.2 cm in height. For the topsoil layer, the amount of soil (same soil used in the subsoil layer, albeit amended) and amendment required for a specific application rate were estimated, mixed, and placed on top of the subsoil layer.

Mixing Organic Amendments: To achieve the target soil OM contents, bulk density and OM contents of the soils and OAs were tested. Bulk density of the composts and biochar were determined as described in the protocol by Washington State University (WSU 2022). Soils bulk densities were estimated only for topsoils in the pot itself. A 10.2 cm depth from the top of the subsoil layer was marked, and the soil was scooped into the pot, uniformly distributed up to the 10.2-cm mark. This bulk density, along with the OM contents of soil and OA (Table 6-8), were used to estimate the amounts of soil and OA required for the specific OM target (Eq. 1). Using these parameters in Eq. 1, the ratio of volume of OA to soil was calculated for a given OA application rate.

$$\frac{V_{OA}}{V_s} = \frac{\rho_s(\theta_t - \theta_s)}{\rho_{OA}(\theta_{OA} - \theta_t)} \tag{1}$$

V_{OA}: Volume of OA added to soil-OA mix
V_s: Volume of soil added to soil-OA mix
ρ_{OA}: Bulk Density of OA
ρ_s: Bulk Density of soil
θ_{OA}: OM of OA
θ_s: OM of soil
θ_t: Target OM of the soil-OA blend

Seed Application: Prior to seeding, pots were randomly ordered to ensure no two replicates or soils of the same kind were adjacently placed. Next, the pots were watered enough to moisten the soil before planting the seeds. A seeding rate of 4.04 g/m^2, equivalent to 0.21 grams of seed mix per pot was applied and gently pressed into the soil to achieve good soil-to-seed contact. The seeds were pre-mixed in bulk at the rates shown in the Table 3-3; therefore, given the small amount (0.21 grams) of seed mix that was added, each pot may not have each seed type uniformly applied.

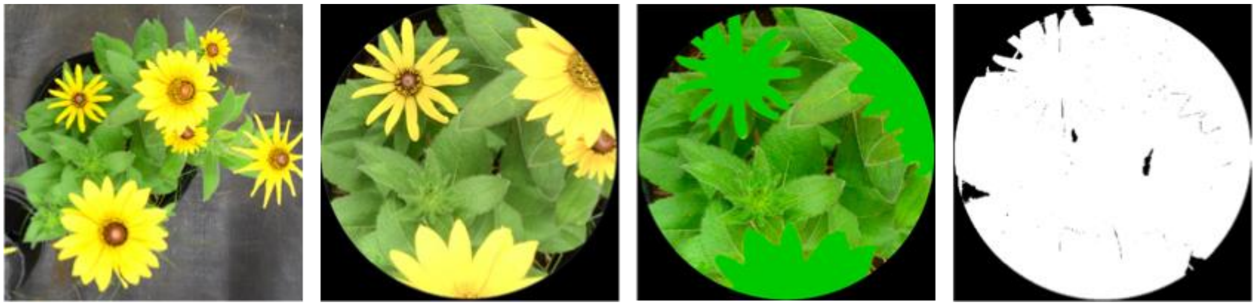
Experimental Conditions and Watering

The required temperatures for warm-season and cool-season grasses can vary depending on the specific plant species. In general, warm-season grasses typically require temperatures between 27 °C to 35 °C during the growing season, while cool-season grasses can thrive in temperatures between 18 °C to 24 °C. Thus, throughout the experiment, the inside temperature of the greenhouse rooms was maintained at 23 °C to 25 °C during daytime and 17°C to 19 °C at night, with a 14-hr photoperiod. Watering events occurred three times a week and the amount corresponded to a precipitation rate of 81.3 cm. Additional water was provided on certain days when it appeared that the plants and soil in the pots were excessively dry.

Pot Study Growth Measurements

Green Coverage: The pot experiment spanned 15 weeks (105 days) after seeding, from Aug 23 to Dec 6, 2022. Images of the pots were captured bi-weekly, starting from week 3 until week 15, in a custom-built image station (Fig. 6-5). LED lights were used to ensure adequate lighting for capturing high-quality images. The image station configuration included an adjustable vertical beam and a camera track slider for horizontal movement. Both the beam and camera track slider are affixed to a vertical track slider, allowing coordinated movement.

To analyze the images for percent green coverage (%GC), a digital image-based software ***Canopeo*** was utilized. This program was created by researchers at Oklahoma State University and can be downloaded as a MATLAB or mobile application (Patrignani and Ochsner 2015). This application converts the green parts of an image to white pixels and the rest of the image area to black. The output is represented as %GC in this study. Default settings of Red/Green (0.95), Blue/Green (0.95) and Noise reduction (100) were chosen for the analysis. Prior to inputting the original images (Fig. 3-2a) into *Canopeo*, the images were preprocessed in Adobe Photoshop 2022, where the images were cropped along the inner diameter of the pot and then as an inscribed square that measures the same edge as the pot diameter (Fig. 3-2b). Since the black-eyed Susan plant species produced yellow blooming flowers, to prevent underestimation of the %GC, they were manually painted green (Fig. 3-2c) as *Canopeo* does not read yellow color. The final measured area is displayed in Fig. 3-2d. Fig. 3-2 details the image processing steps that were followed for estimating %GC.



(a) Original Image **(b)** Cropped Image **(c)** Painted Image **(d)** GC Analyzed Image

Fig. 3-2. Image processing steps followed for %GC analysis

Growth Assessment: Several types of end-of-the-study growth parameters were measured including dry biomass, growth index, plant N, and leaf area. After capturing the final set of pot images (with and without weeds), plant measurements relevant to the growth of black-eyed Susan (BES) were taken. BES was the dominant plant species alongside grasses in the pots. In addition, different amendments had different influences on the morphology of the BES plants. This prompted a more detailed examination of the BES plants in this study. The Growth Index (GI) is a comprehensive three-dimensional parameter calculated as the average of the widest width (x), perpendicular width (y), and height (z) of a BES plant (Norcini and Aldrich 2003). GI of the healthiest looking BES plant per pot was calculated. OAs also demonstrated variability in the color and area of the BES leaves among soil blends (Fig. 3-3). Therefore, plant nitrogen and leaf area were determined on the same BES plant that was evaluated for GI. Plant N was measured by a PlantPen/N-Pen N110 reflectance-based instrument which correlates the chlorophyll (Normalized Difference Greenness Index, NDGI) and nitrogen contents in a plant to estimate *%N*. Leaf Area (LA) of the BES plants was measured using LI-3100C Area Meter. Snipped leaves of the healthiest BES plant per pot were spread on the conveyer belt of the instrument, which then initiated a rotational scan to measure the combined or cumulative *leaf area* in cm^2. Finally, above-ground biomass (weeds not included) was measured after 105 days of growth. Biomass was measured by harvesting the vegetation at the soil level, transfering the shoots into brown paper bags and oven-drying at 50 °C for 48 hours. After drying, the plant material was weighed to report *dry plant biomass* (USDA NRCS 2022).

Fig. 3-3. Differences in color, length, and leaf area of the black-eyed Susan plants between soil blended with turkey litter compost (left pot) vs soil blended with biochar (right pot)

Statistics

All the bar plots and correlation plots were graphed using the mean value for the replicates and the error bars denote the standard deviations among replicates. One-way analysis of variance (ANOVA) was performed for statistical significances (at 95% confidence) among all the treatment groups. T-tests estimated pairwise significances ($p < 0.05$) between two treatment groups or application rates. Linear relationships were determined by Pearson's correlation (R), and the regression analysis was carried out at alpha = 0.05 to determine the probabilistic significance (P) value.

Results and Discussion

Changes to soil pH and EC

Soil pH EC and OM were measured for all the 52 different soil blends that were prepared (see **Error! Reference source not found.**). A significant increase ($p < 0.001$) in soil pH was o bserved when the Biochar (B) amendment was incorporated. The pH of soil-biochar blends ranged from 7.84–8.47 (**Error! Reference source not found.**). This liming effect is due to the primary presence of carbonates and surface organic functional groups in biochar, which collectively contribute to its high pH (Fidel et al. 2017). The T amendment also led to an increase in the pH of the soils (except Sanborn), despite having a slightly acidic pH of 6.8±0.07. When an ammonium source such as the T amendment is introduced into the soils, the ammonium will be released and converted to ammonia gas, which goes to form ammonium hydroxide in the soil solution, consequently increasing the soil pH (at least temporarily) (Pan et al. 2016). In contrast, the pH effects on soils due to compost-based F and Y amendments remained largely unchanged ($p > 0.05$), as they possessed a slightly alkaline pH of 7.65±0.03 and 7.52±0.05, respectively. All the three composts (Y, F and T) statistically increased ($p < 0.001$) the EC in all soils, while biochar showed no noticeable effects. The most substantial increase in EC was due to the T amendment, exhibiting a percent increase ranging from 293-2270%. This was followed by the F amendment (17–725% increase) and Y (4-428% increase) (**Error! Reference source not found.**). Compost sources naturally contain soluble salts and tend to increase the soil EC when incorporated, with the magnitude of it depending on the feedstocks (Li-Xian et al. 2007; Gondek et al. 2020).

Green Coverage

Fig. 3-4 demonstrates the temporal (biweekly) %GC patterns of the vegetation for the various soils and their OA blends. A sigmoid function,

$$y = K_1 * \left(1 + \tanh\left(K_2 * (x - K_3)\right)\right), \tag{2}$$

was nonlinearly regressed to the plant coverage data using the *nlinfit* function in MATLAB's Statistics and Machine Learning toolbox to quantitatively analyze the growth patterns (Table 6-10). In this equation, the variables $K_1, K_2,$ and K_3 represent half the maximum coverage (as %), the rate of growth (in weeks^{-1}), and the half-life (the time at which half the maximum coverage is achieved, in weeks), respectively. The variables y and x denote %GC and the duration of growth time in weeks. A combination of high K_1 and K_2 and low K_3 suggests a greater and quicker establishment of plant cover. Table 6-11 presents the data related to the regression constants ($\mathrm{K}_1, \mathrm{K}_2, \mathrm{K}_3$) estimated for each soil type. Weeds were eliminated from the pots before estimating the final coverage on the 15th week, while the preceding weeks included them. Additionally, the preprocessed images were cropped along the pot's inner diameter, meaning the coverage outside the pot was not accounted for. Therefore, the analysis shown in Fig. 3-4 should be deemed as underestimates in comparison to the "true" vegetation coverage.

Ortonville (O): The greatest final mean coverage (84.9±9.85%) was observed in the OFA soil followed by OBC (82.4±5.47%), OYB (77.2±21.77%) and OBA (73.1±18.56%). The growth curves of the OY blends displayed delayed growth patterns (higher K_3) of the plants compared to the control soil "O", particularly within the initial 9 week-period (Fig. 3-4). However, for two of the OY blends, OYA and OYC, K_2 (rate) was larger than that of the soil "O". The F compost, at lower application rate A, also showed a delay in growth initially but later gained momentum as vegetation started to establish and eventually outcompeted the control. Rates B and C of the F compost, exhibited overlapping plant coverages, but produced lesser vegetation compared to control "O" throughout the study. In contrast, the T compost failed to yield any plants at higher application rates (B and C) even after 15 weeks of seeding. At rate A, the T compost produced a few grass strands with time, covering only 17.4±10.14% of the soil surface after the 15-week period. Alternatively, biochar was the only OA (regardless of its application rates) that outcompeted the control in terms of %GC. While biochar appeared to enhance coverage when mixed into soils, the %GC was not entirely contributed from the planted native species, but rather from the prevalence of weeds, such as Chenopodium album and/or Yellow Wood Sorrel. Although Chenopodium album rapidly grew in the earlier stages, after week 9, these species started to wither in the soil-biochar mixes. Nevertheless, %GC without weeds decreased from week 13 to week 15 in the soil mixes (Fig. 3-4). Given that this clayey soil already possessed an OM of 5.39%, the addition of the OAs did not necessarily contribute to enhanced plant coverage.

Clearwater (C): The control's (C) coverage from the final week was 87.6±5.91%. Growth curves indicated that the B, F and Y amendments consistently exceeded the control's %GC at least until week 11. This was further substantiated by the nonlinear regression constants, which exhibited lower K_3 values (indicating a shorter half-life), with K_1 ranging from 37.9% to 46.7% for plant growth originating from B, F, and Y amended soils, in comparison to the control C. Furthermore, among these amendments, the K_3 for vegetation growth from C-biochar mixtures was the lowest. Consistent with the observations of Ortonville-T soils, the worst Clearwater blends contained the T amendment performed the least optimally. Grass strands were again the only species collected from the CTA blends with 25.4±16.8% GC, and at higher T application rates (CTB and CTC) 0% GC was seen by the end of the study. Clearwater soils had weeds (cleavers) during the study period. However, since cleavers did not densely cover the soils as Chenopodium album did in Ortonville, the presence of weeds in the Clearwater blends had a relatively minor impact on the %GC.

Sanborn (S): The Y amendment at rates B and C had the greatest influence on the Sanborn soil, with SYB and SYC yielding 12.3% and 17.9% (respectively) more GC compared to the control S. This was further supported by the regression constants, K_1 and K_2, which were higher than S, signifying greater coverage and rate. In the case of F amended Sanborn soils, initial plant growth was observed only after week 5, but soon after climbed to 67.9±11.82%, 80.3±13.5% and 72.7±2.32% GC for SFA, SFB and SFC, respectively, by week 15. Similar to the patterns noted in the Ortonville-F blends, the F compost slowed the vegetation establishment when added to the soil; the higher its application rate, greater was the delay. The T amendment also slowed seed germination and growth response (Fig. 3-4), with the final %GC of the STA blend being 86.1±6.9%, placing it right below SYB and SYC at the end of the study. Additionally, the STB and STC growth was slower than STA; but in one of the replicates of each of these soils, the black-eyed Susan surfaced along with other grass species. This led to improved %GC of 43.9±44.3% for STB and 42.3±41.0% for STC, albeit with considerable variability. The growth curves resulting from the Biochar amendment at rates A and B aligned with that of the control soil S. However, at rate C, the established vegetation coverage and rate decreased. Only 3 out of the 39 Sanborn pots (including replicates) developed weeds (yellow wood sorrel and Canada thistle) which therefore did not contribute to the %GC estimates of these soils.

Glenwood(G): GTA is the only amended Glenwood soil that demonstrated greater %GC (87.8±2.41%) than its control counterpart, G (79.6±8.99%) by the end of the study. All other combinations of Glenwood and OAs produced lower above-ground plant coverage than G. Notably, when the T compost was added Glenwood at rate A, it did not experience any growth delays unlike STA, CTA, or OTA, and emerged successful in enhancing this soil for plant growth. GTB and GTC yielded 65.1±7.25% and 54.4±28.64% GC, respectively, again greater in amount compared to the corresponding T rates of other soils. This trend was consistent across all soils: the higher the application rate of T, the lower was the plant yield. The incorporation of biochar at rate A improved the speed of plant establishment; the half-life, K_3, for GBA was 6 weeks ($K_1 =$ 41.7%), in comparison to 7.68 weeks for G ($K_1 =$ 40.3%). Canada thistle was the weed species that prevailed in the Glenwood soils. Coverage dropped between week 13 and week 15 in the soil mixes after removing the weed species (Fig. 3-4).

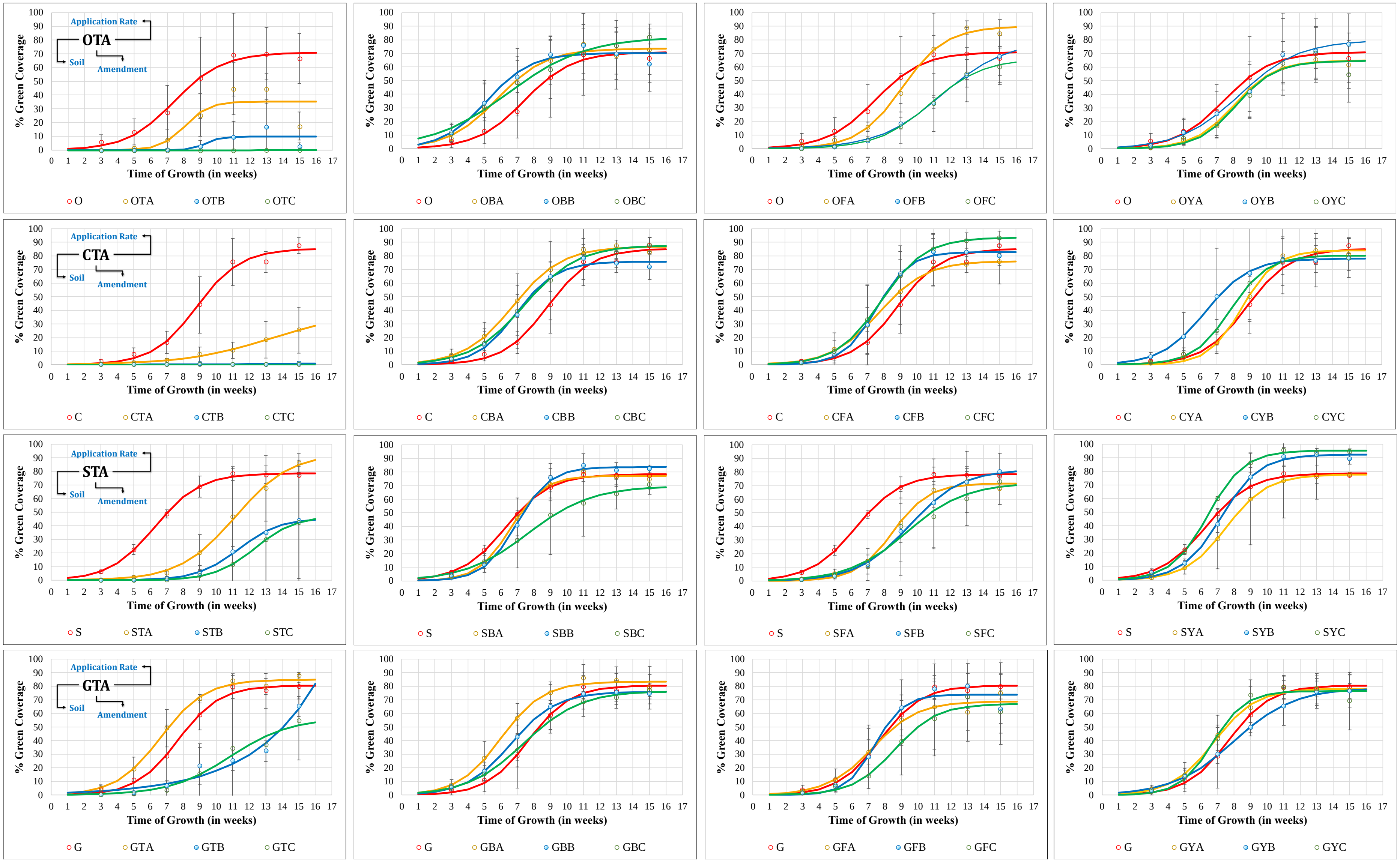


Fig. 3-4. Temporal changes in %GC of soil-OA blends. Note: Weeks 3–13 included weeds in the %GC analysis and week 15 did not.

Correlation between growth and soluble salts content of the soil-OA blends

From the biweekly %GC analysis (growth curves), it was observed that the compost amendments either contributed to delayed or suppressed growth. The latter was particularly noted by the T amendment. To investigate the dependence of plant response to soluble salts, the EC of all 52 soil blends was measured at the onset of the experiment and plotted against the dependent variable (%GC) for every two-week period (week 3 until week 15, Fig. 3-5). Although the means of %GC and EC were charted, the error bars were only added to %GC and not EC for better legibility. A trending exponential decay was observed for the coverage with an increase in the EC content of the soils in the first 7 weeks of seeding. Therefore, the P-value was determined after log transforming the coverage data and a linear regression was obtained. The scatter of the data points is low (R^2<0.6) and a strong statistical correlation ($p < 0.00001$) between the salts content and coverage was noted in the first 7 weeks. As %GC expanded, a linear model was found to be best suited for the data for weeks 9, 11, 13 and 15, with the correlation of determination (R^2) getting higher over time along with high statistical significance ($p < 0.00001$). This switch from exponential to linear correlation between %GC and salts occurred because, with each watering event, the salts would leach from the root zone, making the topsoil layer more favorable for seed germination and growth. Fig. 3-6 gives visual evidence to best compared to the worst performing soil-OA blends. Clearwater soil amended with T at rate C (CTC) did not produce any yield because of soluble salts (EC) of 5137±37.9 μS/cm, even after 15 weeks of seeding. In contrast, Y displayed full-blown coverage when amended into Sanborn at rate C (SYC; EC = 1039±9.3 μS/cm). In general, excess salinity in a soil rhizosphere prompts greater osmotic pressure, thereby limiting the water and nutrient uptake of plants (Hasanuzzaman and Fujita 2022). Overall, soils with EC greater than 2000 μS/cm curtailed plant production to <50% coverage even by week 15.

Compost maturity is related to the plant available N species (NH_4:NO_3 < 1:1), salts (EC < 2000 μS/cm) and pH (6-7.5) (Radovich et al. 2011). T is a concentrated, manure-based compost, which contained a high soluble salts concentration (EC = 15200±440 μS/cm), high NH_4-N (706±74.4 ppm), and high NH_4:NO_3 ratio (24:1) (Table 3-2). Impacts of ammonium toxicity and salt stresses on plant response are well documented when poultry litter is applied (Lu and Edwards 1994; Pan et al. 2016). Soil pH is increased when the T amendment was added to the soils (Table 6-9). This combination of high pH and presence of ammonia gas halts the two-step nitrification process ($NH_4 \rightarrow NO_2 \rightarrow NO_3$) at the nitrite stage. This leads to an accumulation of nitrite in soils and can be detrimental to seedlings, particularly in dry and well-aerated soils (Breuillin-Sessoms et al. 2017; Venterea et al. 2020). Experiments conducted at varying ratios of NH_4:NO_3 demonstrated an impairment of the plant species when NH_4 was the only supplemental N nutrient and greater plant development and yield occurred under sole NO_3 inputs (Saloner and Bernstein 2022). Zhang et al. (2019) provided a suitable NH_4:NO_3 ratio of 25%:75% for desired root biomass and nutrient uptake. Therefore, the combination of greater salts and ammonium contents in T appear to have inhibited the growth and development of the plants.

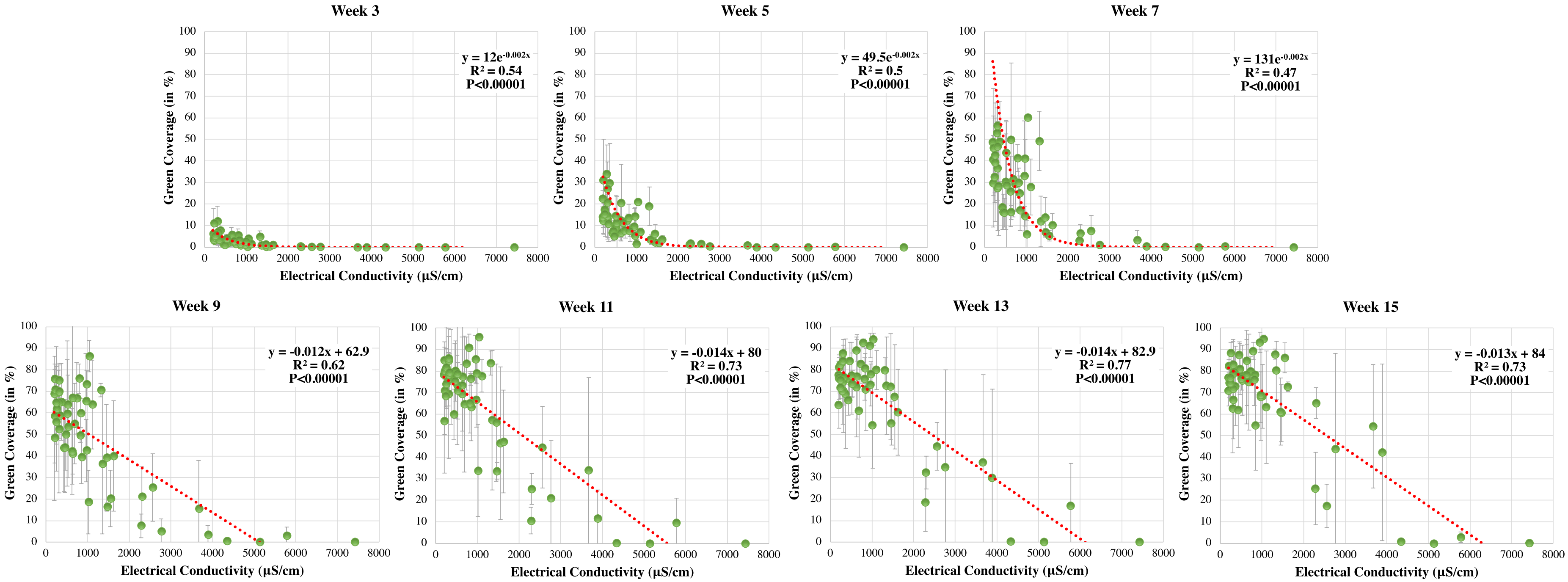


Fig. 3-5. Correlation plots of green coverage vs initial soil soluble salts (EC)

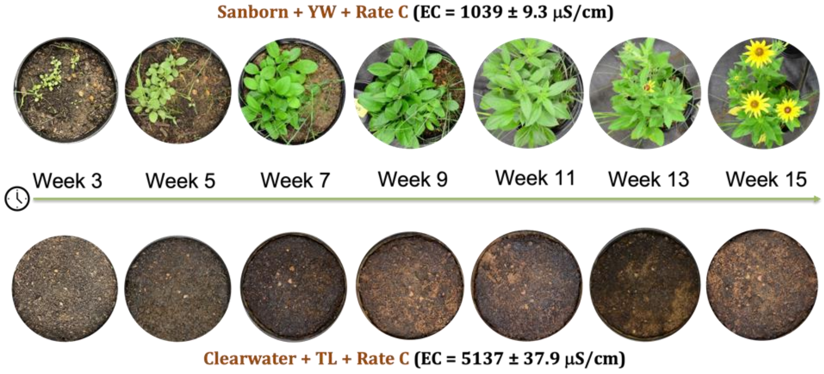


Fig. 3-6. Comparison between one of the best vs worst performing soil-OA blends

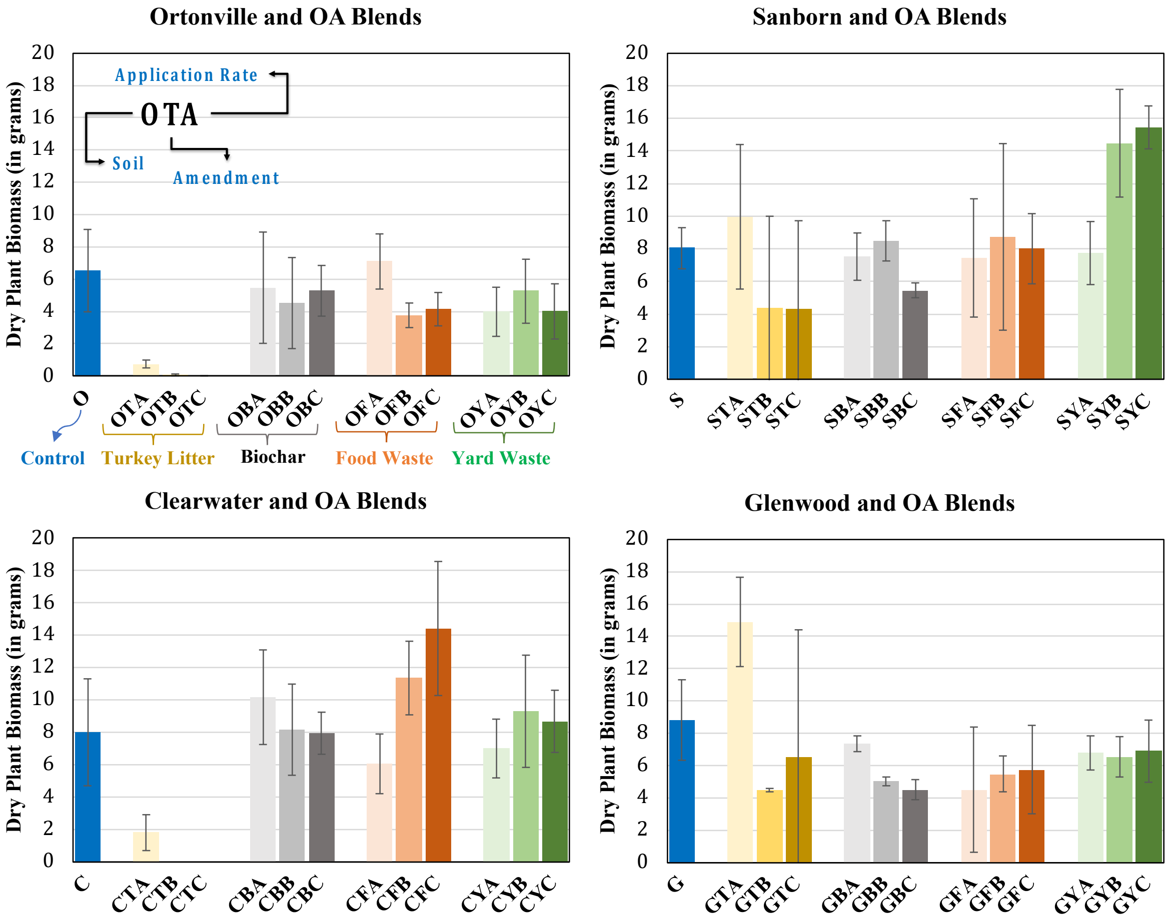
Plant Biomass and Growth Index

Ortonville: Turkey-litter compost was the only OA in Ortonville soil that did not produce plant. Biomass production from all amendments and application rates showed reduced growth compared to the control, O, except for OFA. Weed presence was not reflected in the above-ground biomass, because the measurements did not include them. Growth Index (GI) of BES plants from the Ortonville soil mixes provided similar findings to biomass; the BES GI of did not improve when OAs were added to this soil (Fig. 3-8). Since Ortonville contained acceptable levels of OM (5.39%), it provides greater plant available nutrients than other soils. Thus, the OAs influence on biomass and GI were not clearly observed.

Clearwater: F applied at rates B and C (CFB and CFC) yielded 42.3% and 80.1% more plant biomass compared to the reference soil (C). This increase was followed by CBA (26.9%) and CYB (16.3%), with other amendments showing an increase less than 10%, or reduced growth. The greatest improvement (28.8% increase) in the GI of BES in Clearwater occurred when biochar was amended at rate B. Consistent with biomass, CFB and CFC soils blends positively contributed to an increase of 17.5% and 22.1% respectively in the GI when F was added to the soil. Overall, Clearwater benefitted the most from the F amendment compared to other OAs.

Sanborn: The Y amendment improved the vegetative biomass at higher application rates (B and C) by 1.8 and 1.92 times, respectively, compared to the control S. T at rate A also enhanced above-ground productivity, while rates B and C stunted growth. However, rates B and C of the T amendment produced some biomass (~4.4±5.6 and 4.3±5.4 g respectively) by the end of the study. Sanborn-T blends contained lower salts content compared to the corresponding Ortonville- and Clearwater-T blends. Consequently, they offered a more favorable environment for plant growth.

Although the biomass production was the greatest in SYB and SYC, the BES GI plants in these pots showed statistical improvement ($p > 0.05$) compared to the control soil (S) (Fig. 3-8). However, the GI was positively influenced (STA, 52.1%; STB, 42.1%; STC, 35.4% increase compared to S) by the addition of T. This suggests a morphological advantage to plants when mixed with high N (2.69%, Table 3-2) amendment as long as salts content is not excessively high.


Ortonville and OA Blends

Sanborn and OA Blends

Clearwater and OA Blends

Glenwood and OA Blends

Fig. 3-7. Dry plant biomass (in grams) in soil-OA blends

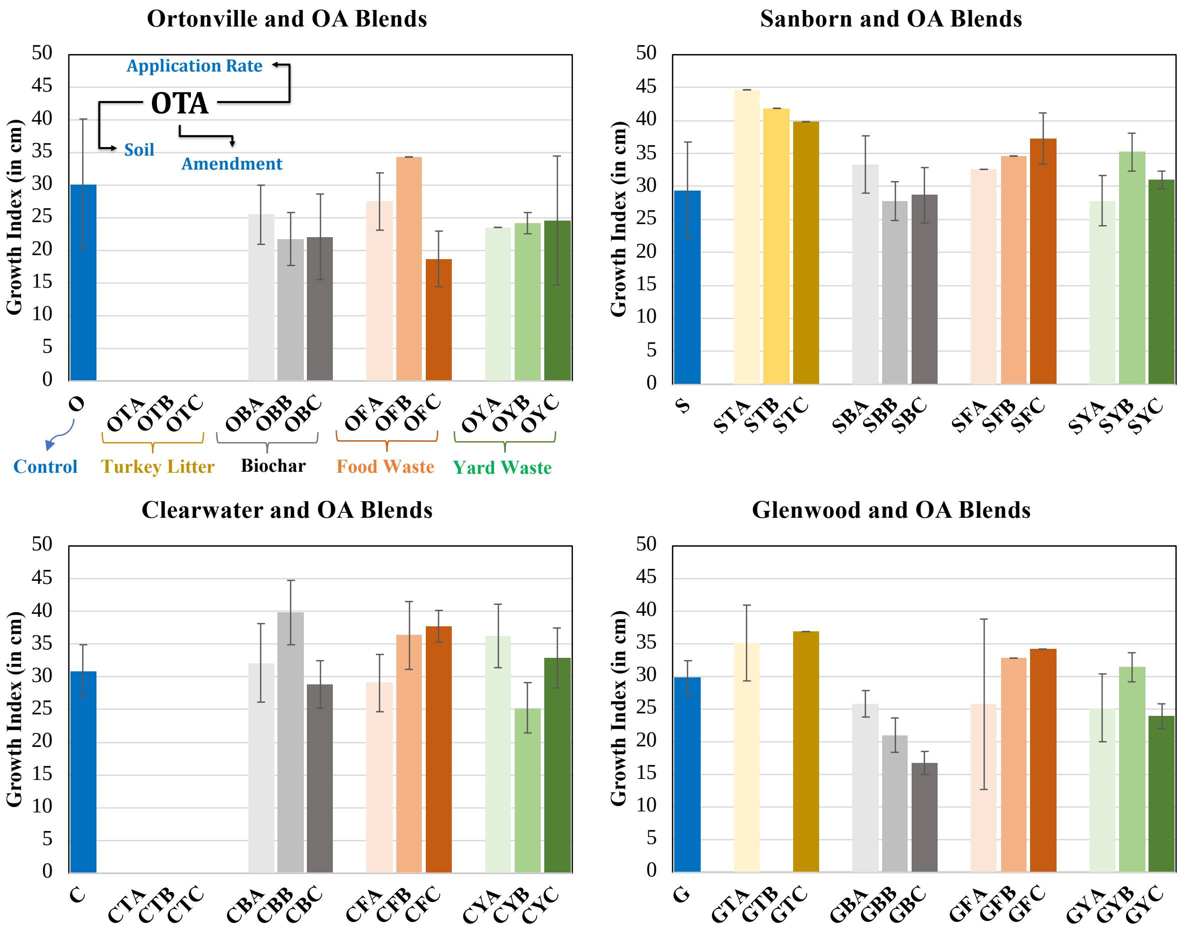


Fig. 3-8. Growth Index (in cm) of black-eyed Susan from soil-OA blends

Glenwood: Except for GTA, which increased the BES GI by 18%, all other soil blends had a negative influence on biomass production in the Glenwood soil (Fig. 3-7). The biochar OA decreased yield by 16.8%, 43%, and 49% at rates A, B, and C, respectively, compared to the control soil (G). Typically, amendments with greater than 24:1 C:N ratio immobilize N in the soil and reducing the plant available fraction (USDA NRCS 2011). Biochar fits this paradigm, meaning amending soils with biochar increases the C:N ratio. This elevation results from the biochar's C:N ratio of 114:1, in stark contrast to the baseline C:N ratio of 10.2:1 found in the unamended Glenwood soil (Table 3-2). Unexpectedly, FW and YW also developed biomass that was 34.9 to 49% (FW) and 21.9 to 26.2% (YW) less compared to G. Although a similar trend of suppressed growth was observed when composts were mixed into the Ortonville soil, the application rates of OA for Ortonville were higher compared to Glenwood, Sanborn, and Clearwater.

Plant Nitrogen and Leaf Area

Fig. 3-9 shows bar plots of %N in the leaves of BES across the soils. Although plant N content was also measured for the grass species in each pot, only the uptake of BES is discussed here as the general trends remained the same between the two plants. Absence of SD error bars on some soil blends (e.g., STA, STB, STC etc.) indicate that only one of the three soil replicates produced BES. The N% in the OAs is T = 2.67±0.09%, F = 1.7±0.07%, Y = 1.39±0.08% and B = 0.67±0.03% (Table 3-2). For all soils, the biochar amendment showed reduced N (also visually less green, Fig. 3-3) in the BES leaves compared to soil-OA mixes and controls (except Sanborn). Sanborn soil contained 0.18% N and the lowest plant available NO_3-N; this lack of plant nutrient manifested in the BES leaves of the control soil (S), noting the lowest plant N (2.3%) (Fig. 3-9). Typically, less than 3% N in plants can induce deficiencies and affect the quality (Plank 1992). In this study, all soils amended with biochar exhibited N deficiencies, with the average uptake levels remaining below 3% (Fig. 3-9). Although biochar produced greater plant coverage in the initial stages of growth, the health of the vegetation (yellowing of leaves, crispy edges, etc.) declined over time, which could be attributed to the poor uptake of macronutrients such as N. Moreover, biochar can also hinder the translocation of P and micronutrients from root to shoot as they get tied up to the organic compounds in the rhizosphere (Alkharabsheh et al. 2021). Of the composts, for at least one rate of application, the BES %N in Y-soil was less than ($p < 0.05$) the corresponding value for F- and T-soil of any soil (Fig. 3-9). Alternatively, the higher plant available N (NH_4+NO_3) content from the T compost prompted the greatest N uptake in the BES plants and grasses of Glenwood- and Sanborn-T amended soils. Saloner and Bernstein (2022) also reported higher N accumulation in cannabis plant with increased NH_4 and NO_3 supply.

Furthermore, the autoclave-citrate extractable (ACE) protein index serves as a valuable soil indicator that can offer beneficial insights into the organic N fraction that can be mineralizable into plant N over time (Hurisso et al. 2018; Geisseler et al. 2019; Sainju et al. 2022). In this study, among OAs, the ACE index is the lowest for B (0.3) and the highest for T (85). The Cornell Soil Health Lab assigned a low-quality rating of 2/100 for B and 100/100 for all three composts in terms of their ACE content. It is noteworthy that, despite plant species emerging in biochar-amended soils, the overall health of the vegetation was subpar, as witnessed by the N uptake results. The growth of vegetation in biochar soils can thus be attributed to the inherent traits of native vegetation, which are adapted to survive under nutrient-limiting conditions (Shivega and Aldrich-Wolfe 2017).

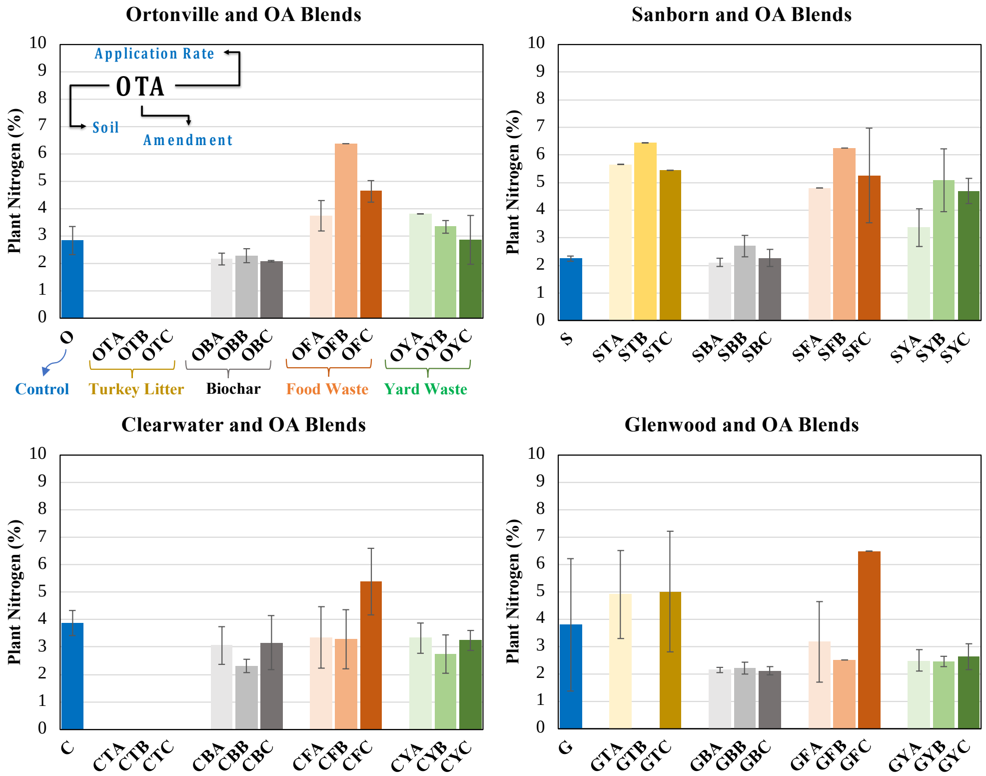


Fig. 3-9. Plant Nitrogen (%) of black-eyed Susan from soil-OA blends

Typically, an increase in the application rate of N should have a positive effect on the morphology of the leaves, i.e., leaf size (length, width, and area) (de Ávila Silva et al. 2021). Taking this lead, the total leaf area of a BES plant with the sturdiest stem per pot was measured. Fig. 6-7 presents the total leaf area data for the amended soils. Similar to the observations made in the N% plots, the N content of the amendments also influenced the leaf area of the BES species. It should be noted that smaller leaf areas, particularly seen in the compost-amended soils, do not necessarily represent the full potential of the growth, because in some pots (e.g., OFC) the BES experienced delayed growth. Visual observations identified smaller leaves and thinner stems of the BES plants from the biochar-amended soils compared to the compost-amended soils (Fig. 3-3). Only two soils (Sanborn and Glenwood), when amended with T grew BES, and the leaves of these plants looked greener and larger compared to other soils.

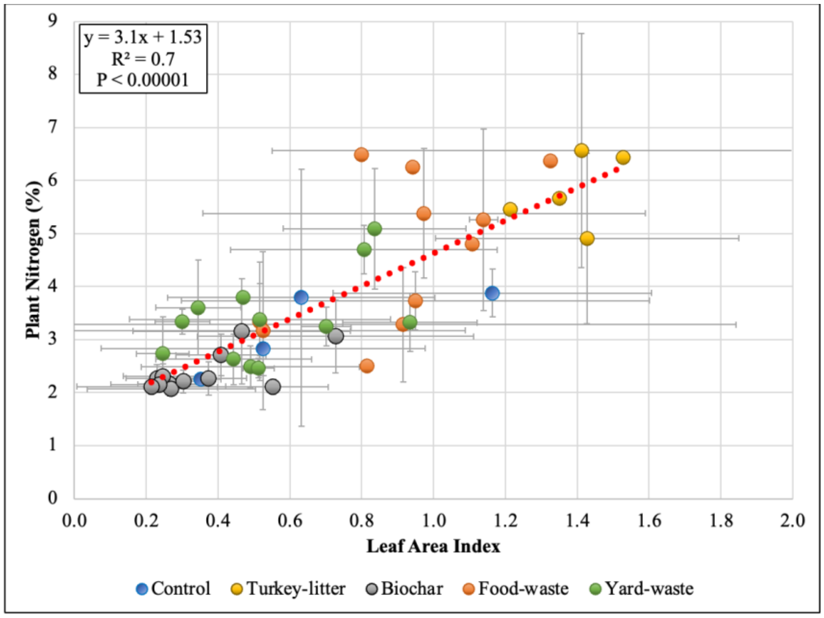


Fig. 3-10. Correlation between plant nitrogen and LAI of the black-eyed Susan plants. Specific colored dots correspond to a particular OA mixed into soils.

The plant uptake of nitrogen is plotted against the leaf area index (LAI) to emphasize the correlation between the two parameters (Fig. 3-10). LAI is a ubiquitously used dimensionless quantity that measures one-sided leaf area per unit ground surface, typically of a canopy (Fang et al. 2019). In this study the LAI is calculated by taking the total foliage of the healthiest BES plant per pot and dividing it by the pot diameter (507 cm^2), which represents the soil surface. Only 44 out of the 52 blends were considered since 8 of those did not produce any BES plants. Also, a replicate of the GTC soil was eliminated when accounting for the LAI and plant N averages because the BES plant in that pot replicate had commenced growth only in the last week of the experiment. This extreme difference in LAI between BES from different replicates of the same soil (GTC) affected the average LAI, therefore forcing the removal of one datapoint from the analysis. Fig. 3-10 demonstrates that plant N is linearly related ($p < 0.00001$) to the plant LAI. Evidence from the past research also noted correlations between leaf area index and the N concentrations in different plant species (de Ávila Silva et al. 2021; Lemaire et al. 2007; YIN et al. 2003). This underscores the linkage between the two parameters, and this empirical relationship enables to determine the unknown variable with the knowledge of the other, in addition to the soil N properties.

Conclusions

Three composts (Y, F and T) and one wood-based biochar (B) were evaluated for rapid and dense native vegetation growth in four topsoils. While it is difficult to recommend optimum soil-OA ratios based on these data, the findings below can be used for choosing the right OA based on information about the amended soils that contributed to poor growth.

1. Coverage results suggest that soluble salts content from the T amendment either delayed or stunted plant growth in the soils. Correlations between GC and EC showed that soils with EC greater than 2000 μS/cm are a deterrent to plant production. Besides salinity, high NH_4 content and NH_4:NO_3 ratio of the T amendment may induce ammonium toxicity and impair plant health.
2. Growth curves showed that faster coverage was achieved in 3 out of the 4 soils in the initial stages of growth when biochar was amended. However, visually, plants growing in the soil-biochar media experienced nutrient deficiencies. This was quantitatively noted through plant N and leaf area measurements which showed that the addition of biochar negatively influenced plant morphology and N uptake. Therefore, plant coverage from soil-biochar blends does not represent the overall plant health,
3. In Sanborn and Glenwood soils, N uptake was higher in the BES plants emerging from the T amendment followed by F and then Y. Also, a similar trend was followed for the LAI of BES in these soils. Greater biomass was accumulated from the Sanborn-Y blends and Clearwater-F blends at higher application rates (>=7.5% OM). Between Y and F, the latter contributed to higher uptake of N and leaf area compared to Y.

The T compost caused plant growth impairments as a result of excess salinity and ammonium toxicity when incorporated into soils to boost the OM content. Consequently, it is recommended to minimize the use of such concentrated manure-based composts for meeting the soil OM specifications of roadside soils. Instead, these composts can be better utilized to improve the soil nutrient contents, similar to fertilizers. Biochar derived from woody materials studied in this research induced N deficiencies and underwhelming foliage cover compared to other OAs and some control soils. To fully capitalize on the benefits of a biochar amendment, it is recommended to enrich wood-based biochar products with complementary nutrient fertilizers to support long lasting and healthy vegetation. Although a delayed plant growth was observed in soils amended with F and Y composts, they can continue to release plant nutrients for a sustained period while maintaining healthy vegetation. Since overapplication of composts can cause stormwater quality issues, it is important to incorporate F and Y composts at controlled levels (less than 10% by weight), in soil management practices.

Acknowledgements

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CHAPTER 4. SCALING UP THE IMPACT – A MESOCOSM EVALUATION OF COMPOST AND BIOCHAR AMENDMENTS ON SOIL PROPERTIES, VEGETATION GROWTH AND WATER QUALITY

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Abstract

Compost amendments are apparent for excessive nutrient release, and when used as a soil amendment or a blanket on roadsides, it may further contribute to eutrophication of natural waterbodies. This study proposes regulating compost's use by combining it with a pollutant-adsorbing material – biochar. The experiment focused on the large-scale integration of biochar and compost into soils, analyzing their combined effects on soil properties, water quality, and plant growth. Large mesocosms were designed to replicate roadside embankments in the UMD Greenhouse facility. Four amended soils were created: one with only compost (CY), one with only biochar (CB), and two mixtures of compost and biochar in specific ratios – 75% compost and 25% biochar (C3YB), and an equal mix of 50% compost and 50% biochar (CYB). The aim of these amendments was to increase the base soil's organic matter content to 6.5%. Twelve weekly simulated rainfall events were applied, each with a depth of 2.54 cm. The study found that CY soil enhanced plant growth more effectively than other treatments. Compost-biochar mixtures (CYB and C3YB) also improved plant growth, especially with higher compost ratios. Regarding effluent water quality, compost increased nitrogen (N) levels, whereas biochar reduced them. Compost-biochar mixes with more biochar showed lower N export as well. In plant tissue, higher N was

observed in compost-amended soils (CYB, C3YB and CY), but biochar (CB) indicated N deficiencies. Phosphorus (P) levels in effluents were highest from CY soil as well, whereas CB soil could effectively retain the influent P. In terms of plant health, biochar's inherent phosphorus content and moisture retention properties increased P availability to plants. The more biochar in the mix (CYB), the higher the plant P and lower the effluent, achieving a balanced outcome. Additionally, amended soils showed reduced soil erosion (suspended solids) compared to the control soil. Overall, the study suggests that compost-biochar mixtures can be a sustainable approach to achieving environmental goals, balancing nutrient management, and promoting plant growth.

Introduction

Low-grade urban soils are predisposed to erosion and cannot actively mitigate stormwater related issues. It is very important for state departments of transportation (DOTs) to take steps towards vegetating highway shoulders by rapidly remediating urban soils through sustainable best management practices. This prompted the drive and motivation for transportation agencies to use organic amendments (OA) like compost or biochar over the past decade. Most OAs are inexpensive, widely available and provide great nutritional and structural benefits to urban soils, which typically are bereft of nutrients and soil stability. Application of OAs to soils increases the soil organic matter (OM) content, buffers soil pH, supplements plant nutrients, and improves water holding capacity and infiltration (Agegnehu et al. 2015; Glaser and Lehr 2019; Kranz et al. 2020). Besides this, depending on their constituent source elements, OAs have the potential to treat stormwater contaminants (Kaya et al. 2022; Qi et al. 2023).

While the application of OAs seems positive from vegetation and hydraulic standpoints, previous research has raised concerns around the use of such nutrient-dense organic materials (composts) due to excessive nutrient leaching, which may worsen the existing problem of stormwater pollution. Studies that analyzed runoff quality from topsoil amended with dairy-manure compost and biosolids (Puppala et al. 2011), and green-waste (yard trimmings and grass clippings-based compost) and biosolids compost amended topsoils (Owen et al. 2021) showed that the nutrient constituents (phosphorus and nitrogen) were high in the amended topsoils compared to the controls. This loss of nutrients to surface water can impair downstream waterbodies and worsen eutrophication related issues.

Biochar is another widely endorsed soil amendment and it is produced by thermal combustion of biomass in an oxygen-deficit environment (pyrolysis) (Lehmann and Joseph 2015). The structure and stability of the biochar product depends on its feedstock sources (e.g., animal manure, wood waste etc.,), pyrolysis temperature, and heating rate. Biochar addition has proven to be an effective soil remediation strategy, sequesters carbon, improves soil porosity, adsorbs contaminants, and enhances stormwater quality (Kaya et al. 2022; Lehmann and Joseph 2015). However, some studies revealed that biochar can contribute to P release particularly at lower (and environmentally relevant) loadings of P (Xu et al. 2014; Yao et al. 2012). However, feedstock sources are critical to this assessment. For example, biochar derived from wood does not free up P from the soils which is a benefit in the context of water quality, revealed a meta-analysis (Glaser and Lehr 2019). Additionally, this analysis also indicated elevated availability of P followed by biochar addition, particularly in acidic and neutral soils (Glaser and Lehr 2019). On the other hand, some biochar amendments, particularly those made from wood waste, can lack plant-available nitrogen and may limit vegetation (Agegnehu et al. 2017; Singh et al. 2010). Since N is typically the limiting nutrient in soils, it is therefore advised to supplement biochar with an N fertilizer for plant productivity.

The singular contributions of adding compost or biochar to soils has been extensively evaluated for crop productivity and nutrient leaching. However, new research has shifted in the direction of testing the combined effects of compost and biochar mixtures as a prospective strategy for soil remediation. Research has provided evidence of reduced nitrate (NO_3) and phosphorus leaching and improved yield in soils amended with biochar and compost together (through water and nutrient retention) compared to non-amended control soils (Agegnehu et al. 2015; Cao et al. 2018). Contrarily, Iqbal et al. (2015) noted no significant benefit to adding biochar to compost in bioretention soils in reducing ortho phosphate (PO_4) and NO_3 leaching. In their literature review, Agegnehu et al. (2017) found the popularly used biochar in research is derived from woody materials, and there is a paucity of research in understanding biochar-compost integrated soil systems in large field-scale experiments.

The goal of this project is to test the synergistic effectiveness of compost-biochar mixtures in reducing nitrogen and phosphorus leaching due to compost additions, and in improving vegetation growth and quality. To the best of the authors' knowledge, this study is one of the first, if not the first, efforts in evaluating biochar and compost-amended soils in a large mesocosm experiment with slope considerations, mimicking roadside embankments. Given the concerns of composts in terms of water quality (CHAPTER 2) and wood-derived biochar in terms of vegetative health (CHAPTER 3), this study hypothesizes that a mixture of compost and biochar incorporated into soils can improve soil fertility and plant uptake of nutrients, all while minimizing nutrient losses to infiltrated or surface waters. The findings may indicate a potential use of compost and biochar mixes in topsoil remediation to control erosion and improve stormwater quality.

Experimental and Analytical Methods

Materials

The soil (S) used in this study was sourced from a project site managed by the Minnesota Department of Transportation (MnDOT) located in the Sanborn region of Minnesota. This soil is classified by USDA as *Sandy Loam* and has an OM content (loss on ignition) of 4.2±0.14% (Table 4-2). Since the soil falls within the accepted range of 3-15% OM common to many DOT topsoil specifications, it was decided to reduce the soil's OM by mixing it with sand. This resulting control soil (C) therefore contained 67% Sanborn, 12% medium (0.8-0.3 mm) sand and 21% fine (0.6-0.2 mm) sand. These proportions were determined to ensure that the particle size distribution of the original Sanborn soil was not significantly altered (see Fig. 6-8). The OM (loss on ignition; LOI) content of the C soil was then measured to be 2.62±0.05%.

One compost produced from *yard waste* (Y), and one *wood-derived* biochar (B) were chosen for this study. The former was obtained from *The Mulch Store* and the latter was shipped from the *American Biochar* company. The biochar's composition is 100% wood biochar and feedstock are southern yellow pine species. A previous study that evaluated organic soils containing 6% OM noticed desired grass growth without any adverse effects on water quality (Pamuru et al. 2024). Therefore, the OAs were incorporated (independently and together) into C to increase the soil OM content to 6% approximately. The six media included Sanborn soil (S), control soil (C), control amended with Y (CY), control amended with B (CB), control amended with 50% C and 50% B (CYB) and control amended with 75% Y and 25% B (C3YB). The soil, sands and OAs were mixed on dry-weight basis to achieve their target OM%. The amounts of each material were estimated from the linear regression constants plotted between soil OM% vs percent addition (by weight) of each OA to control soil (Fig. 6-9).

Greenhouse Experiment and Measurements

The growth experiment (July 3 – Oct 3, 2023) was conducted in the University of Maryland (UMD) research greenhouse facility. Six identical boxes were constructed that are 1.8 m in length and 0.46 m in width. The boxes are inclined at an engineering slope of 2:1 to replicate roadside field conditions. The inside of the box was lined with a single-sided textured geomembrane to create a friction surface that prevents the soil from sliding down the box given its steep slope. Additionally, at the bottom end of the box, a vinyl micro-filter mesh along with a metal mesh gutter guard were securely attached to contain the soil within the box.

The soil layer was packed to a depth of 0.1 m (4 in) normal to the base of the box. Within the soil layer, METER Group's TEROS 12 sensors, which measure soil moisture content, electrical conductivity, and temperature, were embedded at a depth of 0.05 m (halfway). In order to ensure good soil-sensor contact, approximately 5 kg of the corresponding soil type was passed through a #4 sieve, slightly wetted and firmly packed around the sensor needles, and carefully positioned into the soil. For soils C, CY, and CB, five sensors were randomly places along the soil bed, while CYB, C3YB, and S soils each received only four sensors per box. Once the sensors were randomly placed, the remaining half of the soil was emptied into the box and packed down to 0.1 m depth. Each soil was then uniformly seeded with native plant species (a mixture of forbs and graminoids) at an application rate of 4.04 g/m^2. Details regarding the seed mix and their individual application rates can be found in Pamuru et al. (2024). A double-layered erosion control blanket (AEC Premier Straw® Double Net FibreNet™), sourced from American Excelsior, was placed on top of the soils after seeding to minimize erosion due to the steep slope.

One 12.7 mm HH-30 W SQ Fulljet® nozzle connected to the tap water outlet was centered between two boxes, at a height of 2.8 m above the ground, and used as the rainfall simulator. The soils were subjected to a series of 12 weekly rain events (between Jul 3 – Oct 3, 2023). Each rainfall was applied to a depth of 2.54 cm at an intensity of 10.16 cm/hr. The experiment setup in the greenhouse is shown in Fig. 6-10. and the water quality analyses included pH, electrical conductivity (EC), total suspended solids (TSS), total organic carbon (TOC), total nitrogen (TN), nitrate + nitrite (NO_x), ammonium (NH_4), total phosphorus (TP), total dissolved phosphorus (TDP), and orthophosphate (SRP or PO_4). The list of water quality parameters and their corresponding analytical methods and detection limits are given in Table 6-13.

Pictures were taken (approximately from 2.44 m above the ground) weekly starting at 21 days after seeding to estimate the percent green cover (%GC) for the soils. This was done by utilizing a digital image-based software called *Canopeo* (Patrignani and Ochsner 2015). The %GC was estimated under the default settings of Red/Green (0.95), Blue/Green (0.95) and Noise reduction (100). The pictures were cropped along the inner edges of the box on *Adobe Scan* before calculating %GC. Fig. 6-11 presents the image processing steps that were followed for measuring weekly %GC using *Canopeo*.

End-of-study plant measurements included measuring black-eyed Susan (BES) leaf area, dry plant biomass, and total plant tissue analysis (N, C, P and micronutrients). The total leaf area (LA) of the BES plants was determined on an LI-3100C Area Meter. The above-ground plant biomass was collected into brown paper bags and oven-dried at 50 °C for 48 hours, to record dry plant biomass (USDA NRCS 2022). The dried plant matter was then ground using a Wiley Mill Model 3383-L10 (Swedesboro, NJ) and passed through a #40 mesh. The ground matter was measured for C and N on a LECO CN628 analyzer (LECO corporation) at UMD. Additionally, plant tissue samples were sent to the Cornell Soil Health Laboratory for P and micronutrients analysis (EPA Digestion Method 3050).

After the growth period, a total of 9 soil cores were collected from each box, with 3 cores taken from the top, middle, and bottom 0.61-m sections, respectively, for chemical analysis. Soil properties pre- and post-growth were analyzed at UMD Environmental Engineering Laboratories for pH, EC, OM%, C, N, plant available N (PAN), Olsen-P, Mehlich-3 P and micronutrients to assess for soil fertility. Information pertaining to soil chemical analysis is presented in Table 6-12, and the soil and OA properties are given in Table 4-1 and Table 4-2.

Bench-scale Adsorption Test

A batch adsorption experiment was conducted, employing a test setup similar to that used in (Lei 2024), to determine the adsorption capacity for inorganic phosphorus (PO_4) of biochar amendment, control soil (C), and control + biochar (CB). Initially, a 0.01M KCl solution was prepared as a diluent. A range of phosphorus concentrations (0, 0.05, 0.1, 0.25, 0.5, 0.75, 1, 2.5 and 5 mg-P/L) was made by diluting a 1000 mg/L PO_4 as P stock standard in the KCl solution. 1 gram of media was mixed with 50 ml of the prepared phosphorus concentrations in the centrifuge tubes. The tubes were subsequently shaken using an end-over-end shaker. During the initial 4 hours of the experiment, the pH of each water-media mixture was adjusted to 8.8±0.1 (an approximate average of the media/water mixes) using 0.1M HCl and 0.1M NaOH. After 24 hours of shaking, the final pH of the mixes was recorded. Subsequently, the mixtures were centrifuged, a colorimetric analysis for PO_4-P was carried out of the supernatants using the SEAL AQ300 Nutrient Analyzer, at a wavelength of 600 nm.

Statistics

Since there were no experimental replicates, three sub-samples were collected from each sample and subjected to the respective water/soil/plant quality analysis to ensure adherence to

QA/QC. In cases where applicable, the average and standard deviation were calculated to illustrate variability among (method) replicates. To assess the dependency between two groups, Pearson's correlation coefficient (R), and regression analysis was conducted at a significance level of alpha = 0.05 to determine the probability significance (P) value.

Table 4-1. Chemical analyses of the six study soils

Property	Units	Sanborn	Control	CY	CB	CYB	C3YB
pH	-	7.93±0.01	8.23±0.05	8.01±0.02	8.39±0.08	8.23±0.03	8.12±0.02
EC	µS/cm	292±3.58	208±2.38	789±97.46	227±6.87	457±7.44	628±14.6
OM (LOI at 440 °C)	%	4.2±0.14	2.62±0.05	6.84±0.31	6.46±0.12	6.68±0.36	7.17±0.16
C	%	2.4±0.23	1.45±0.04	3.62±0.42	6.1±0.7	4.77±0.43	5.01±1.25
N	%	0.17±0.02	0.09±0.004	0.27±0.03	0.12±0.003	0.21±0.02	0.28±0.04
C:N*	-	14.2	15.5	13.3	52.4	23	17.8
PAN	mg-N/kg	49.4±0.34	33.6±0.62	67.2±1.89	23.6±0.36	39.5±0.64	53.1±0.93
Olsen-P	mg-P/kg	6.9±0.46	8.61±1.34	36.8±2.76	10.24±0.16	24.9±0.74	31.6±2.12

All values are denoted as Mean±SD of three representative samples.
*C:N ratio is calculated using the means of C% and N% respectively, hence SD is not included

Table 4-2. Chemical Analysis of the two study organic amendments (OA)

Property	Units	Biochar (B)	Yard-waste Compost (Y)
pH		9.42±0.08	7.52±0.05
EC	μS/cm	801±46	3040±219
OM	%	68.9±1.3	31.7±2.16
C	%	76.7±1.31	18.4±0.88
N	%	0.67±0.03	1.39±0.08
C:N*		114	13.3
NO_3-N	mg-N/kg	4.32±1.26	38±12.4
NH_4-N	mg-N/kg	7.14±3.68	46.8±3.09
Org-C/Tot-C‡	%	78.4	97.5
Extractable P‡	mg-P/kg	599	572
Surface Area¤	m^2/g	329	NA

All values are denoted as **Mean±SD** of three representative samples.
*C:N ratio is calculated using the means of C%, N% and NH_4, NO_3, respectively, hence SD is not included
‡Measurements for organic carbon fraction of total carbon (Org-C/Tot-C) and extractable phosphorus for the OAs were obtained from Cornell Soil Health Laboratory using the (Modified) Morgan soil test method (Fig. 6-16 and Fig. 6-17)
¤Surface Area of biochar was provided by NAKED Char® Activated Biochar (Fig. 6-18)
NA: Not Applicable

Results and Discussion

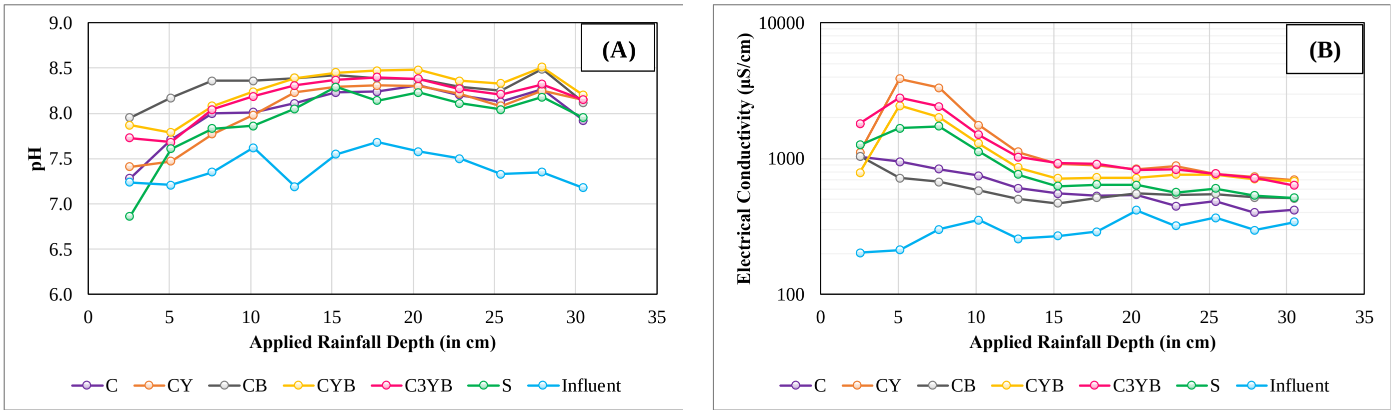
Water Quality

Background Constituents

As evidenced by the data pertaining to soil pH and EC, it is discernible that addition of biochar (due to its oxygen functional groups) led to a concurrent increase in soil pH, while incorporating the yard waste compost (due to the presence of mineral salts) amendment resulted in an elevated EC (Table 4-2). These observed trends were likewise reflected in the effluents of the soil samples. The pH followed the order: CB > CYB > C3YB > C > CY > S, while the EC displayed this trend: CY > C3YB > CYB > S > C > CB, particularly during the initial rainfall events (Fig. 4-1A and

Fig. 4-1B). Additionally, the pH of all soil effluent samples rose with each successive rain application, eventually reaching a plateau by the end of the study. This increase occurs because of the plant uptake of nutrients (e.g., uptake of NO_3 releases OH^- ions), and as vegetation establishes, the inherent (or amendment driven) buffering capacity of the soil stabilizes the pH (Lea-Cox et al. 1996; Marschner 1995). In contrast, the EC displayed a decline over time. Given the sloping nature of the soil bed, rainwater (influent) can percolate through and/or runoff down the slope, carrying along free soluble ions, thereby washing away the salts from the soil surface.

At the onset of the experiment, the soil mixes were initially dry, which caused lower runoff volumes compared to other rainfall events (2-12). However, these initial conditions led to higher sediment content in the runoff samples in the first 2.54 cm of rainfall (Fig. 4-1C). As the experiment progressed, the amendments had a positive impact on sediment transport, where beyond the first rainfall, the maximum TSS concentrations were 12.8, 15.6, 18.6, and 27.6 mg-TSS/L for CYB, CB, C3YB and CY soils, respectively, across all rainfall events. The maximum TSS in the S runoff was also comparable at 22.6 mg-TSS/L. The control on the other hand, due to the incorporation of sands and initially lacking vegetation, experienced greater sediment loss than others. But the concentrations dropped down to 9.7 mg-TSS/L by the end of the study.



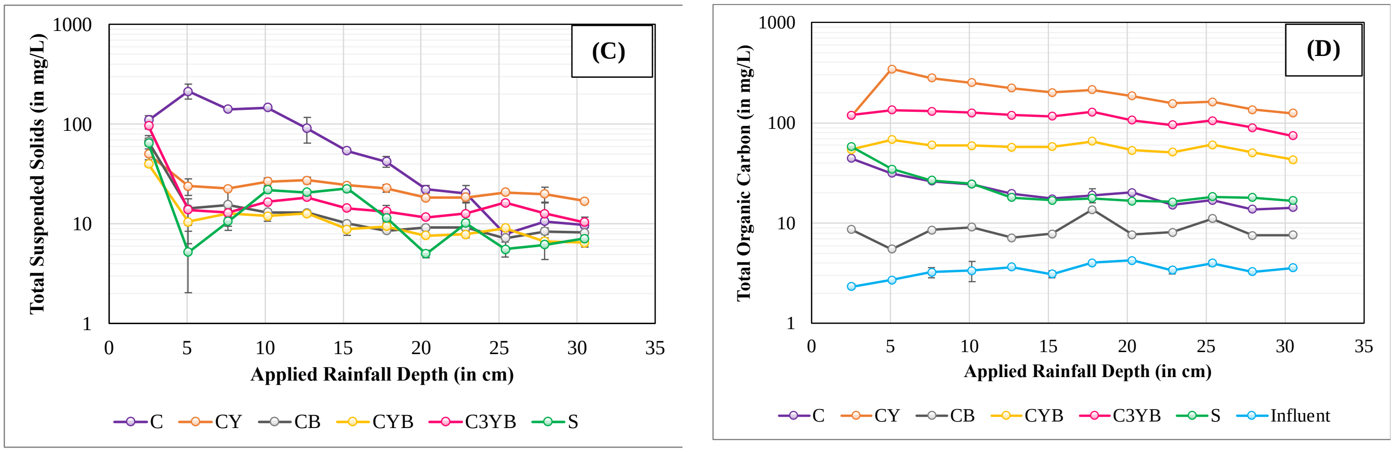


Fig. 4-1. Changes in concentrations of **(A)** pH, **(B)** Electrical Conductivity (μS/cm), **(C)** Total Suspended Solids (mg/L) and **(D)** Total Organic Carbon (mg/L) in soil effluents with increase in rainfall depth

The Fig. 4-1D depicts that all soils released more TOC compared to the influent tap water concentrations. When comparing soils, the addition of biochar to the control soil reduced the TOC in the runoff, which remained under 10 mg-C/L throughout the experiment. S and C showed similar TOC export patterns. Soils amended with compost consistently exported the highest TOC levels across all rainfall events in the following order: CYB > C3YB > CY following the amount of compost added. The effluent samples from the amended soils displayed distinctive colors depending on the type of amendment (biochar or compost) that was added to the soil (Fig. 4-2). The biochar effluents contained some fine black particles, but mostly appeared clear resembling the tap water influent. In contrast, the compost amended soils (CYB, C3YB and CY) exhibited hues of orange, with soil containing only compost (CY) showed the darkest orange color. The color gradient between soils with biochar (CB), 1:1 compost-biochar (CYB), 3:1 compost-biochar (C3YB), yard waste compost (CY) was evident. The presence of organic compounds (tannins or other pigments) can explain the color of these compost effluents (Chatterjee et al. 2013; Mohammadipour et al. 2021). The organic carbon content in the leachate therefore served as a surrogate indicator for understanding the quantity of organic compounds present.

Fig. 4-2. Influent (tap water) and effluent samples collected after simulated rainfall event #12

Nutrients in effluent

The data on nitrogen and phosphorus from the collected effluent samples are presented in Fig. 4-3 and Fig. 4-5. In the case of nitrogen, the original topsoil (Sanborn) possessed a low C:N ratio (14.2:1) and a total nitrogen of 0.17% (typical to agricultural soils; Horneck et al. (2019)) (Table 4-2). As a result, the runoff total nitrogen concentrations in the early stages of the rainfall events from S exceeded 100 mg-N/L (Fig. 4-3A). The incorporation of sands to make the control soil led to a decrease in the overall nitrogen content of the soil. Therefore, in comparison to S, the control effluent exhibited lower nitrogen concentrations throughout the entirety of the experiment (Fig. 4-3A). Contrasting impacts of compost and biochar on runoff N were noted. The CY soil released nitrogen akin to that of S, but higher than that of the control soil's runoff. Biochar, on the other hand, started at 76.8 mg-N/L during the first flush, decreased to <1 mg-N/L, approaching the influent concentrations at the end. The compost-biochar mixed soils, CYB and C3YB, also showed benefits in reducing the runoff nitrogen due to the presence of the biochar amendment. The N content in the runoff from the compost-biochar mixtures depended on the proportions of the amendments; the higher the compost content, the greater the nitrogen release, and vice-versa with biochar (Fig. 4-3A).

Speciation results indicated that the nitrate + nitrite (NO_x) fraction, the mobile form of nitrogen, was prevalent across all soil effluent samples, particularly in the initial rainfall events

(Fig. 4-3B). However, as the NO_x levels decreased over time, the TON became the dominant form in the later rainfalls, particularly noted in compost amended soils (CYB, C3YB and CY). The fractional magnitude (not concentrations) of TON in runoff increased with increasing compost composition and constituted 92.1%, 94.9%, and 95.9% of TN, for CYB, C3YB and CY, respectively, after 30.5 cm of applied rainfall. Greater export of TOC (also evidence by dark orange color of the compost amended soils) from the compost in the runoff samples likely contributed to the organic N release. Ammonium and nitrite concentrations were measured for rain events 1, 2, 6, and 12, but were always below the detection limits of 0.01 mg-N/L.

The C:N ratio of the soils is a robust indicator that controls the losses of mobile nitrogen. The total mass exported (in mg/m^2) of NO_x-N and N from the soil effluents (Sanborn was excluded to keep the base soil composition consistent) were plotted against their respective soil C:N ratio, which demonstrated an inverse relationship (a decaying power function) with a coefficient of determination $R^2 = 0.98$ and 0.93, respectively. This trend has also been observed in other studies (Adams et al. 2005; Pamuru et al. 2024). Further, it is important to note that a significant fraction (78.4%) of biochar C is organic (labile and recalcitrant) (Table 4-2). Bakshi et al. (2018) assessed biochars with different feedstock materials for labile and recalcitrant fractions of C and N. In their analysis, it was revealed that hardwood biochars had a high average labile C:N ratio compared to other herbaceous feedstocks, which leads to immobilization of the mineralizable N (NO_x or NH_4^+) in the soil as microbes utilize it for their nutritional needs. In addition, biochar is relatively low in nitrogen content, which could have further minimized N export (Table 4-1).

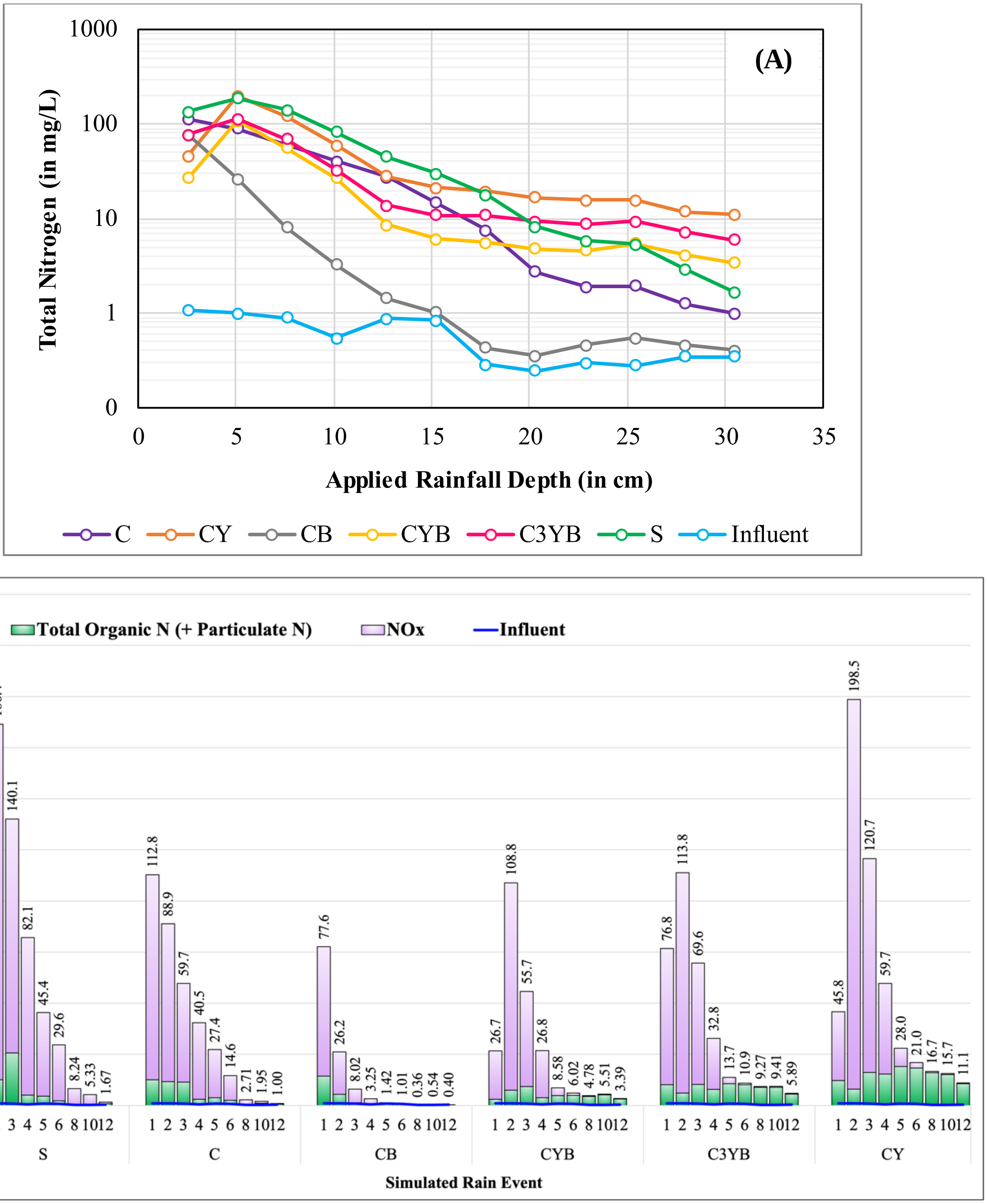


Fig. 4-3. (A) Changes in concentrations of TN (in mg/L) in soil effluents with increase in rainfall depth. **(B)** Distribution of N species in soil effluents with increase in rainfall depth

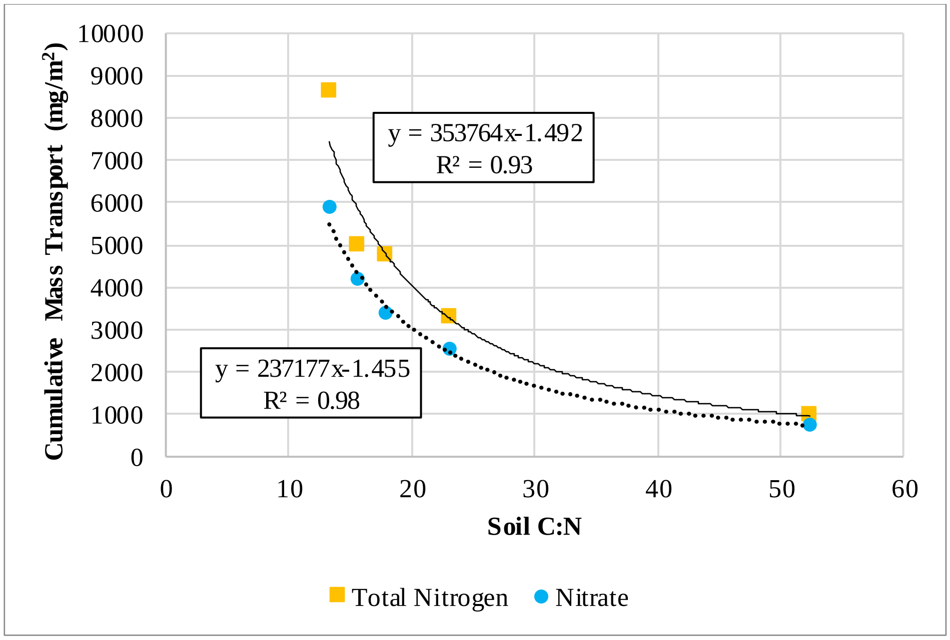


Fig. 4-4. Cumulative Mass Transport of Nitrogen vs soil C:N ratio (Sanborn excluded)

Soils S, C and CB retained phosphorus, releasing concentrations lower than the influent TP in their steady state (Fig. 4-5A). A first-flush of P was noticed in the S and C effluents. The former (S) attained a rapid steady state after the first 2.54 cm of rainfall, while the latter (C) gradually reduced and levelled off after applying 25.4 cm of rainfall. In contrast to nitrogen, which consistently decreased over rain events, phosphorus (especially from that of soils with compost present) did not exhibit a distinct pattern but maintained consistent elevated releases throughout the study (Fig. 4-5A). Introducing biochar to compost-amended soils (CYB and C3YB) positively influenced the water quality, by reducing TP concentrations compared to CY. As the biochar's fraction in soil OM% rose, the phosphorus concentrations in the C3YB and CYB effluents declined. TP concentrations for CYB, C3YB and CY ranged between 0.51-0.81 mg-P/L, 0.64-0.93 mg-P/L and 0.89-1.28 mg-P/L respectively, higher than the influent levels.

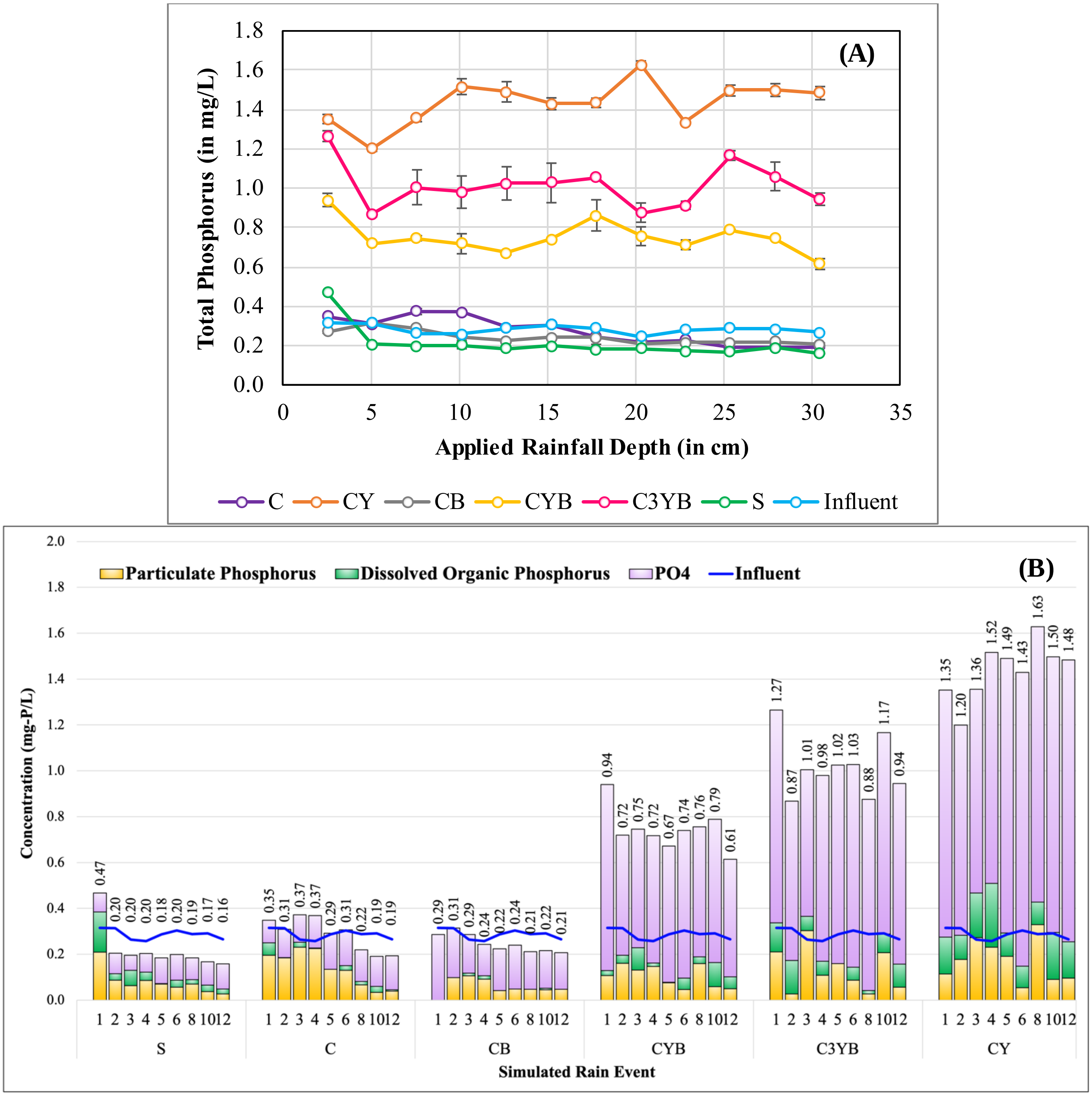


Fig. 4-5 (A) Changes in concentrations of TP (in mg/L) in soil effluents with increase in rainfall depth. **(B)** Distribution of P species in soil effluents with increase in rainfall depth

The speciation results shed light on the phosphorus forms in the soil effluents as affected by the organic amendments. The distribution of three important forms of phosphorus, PP, DOP and PO_4, is displayed in Fig. 4-5B. The blue line in the bar plots represents the influent TP across rain events. PP comprises both organic and inorganic particles, often linked with runoff sediment. The control soil (C) experienced the greatest sediment (TSS) loss among others. The correlation between TSS and PP in the C effluent was positive (R=0.87) and significant ($p < 0.05$). Besides C, the S effluent also showed a strong correlation (R=0.9) between TSS and PP. However, for the amended soils, this correlation was not significant, potentially because of low TSS (<25 mg/L) concentrations. Over time, the DOP levels in the C, S and CB effluents dropped, leaving only PP and PO_4 in the effluent. The presence and magnitude of DOP in the compost-amended soil runoff (CYB, C3YB and CY) grew with an increase in the compost application. This is a concern because the organic phosphorus in runoff can mineralize into soluble phosphates (bioavailable forms) in receiving water bodies, exacerbating eutrophication (Torrent et al. 2007; US EPA 2013b; Zhang 2019). This underscores the ecological significance of organic nutrients (P and N) in the soil runoff due to the compost amendment.

PO_4 is the plant-available and soluble reactive form of phosphorus. The influent contained 0.26-0.32 mg-P/L, present as PO_4 and the influent PO_4 retained in S, C, and CB ranged between 58.4-74.8%, 44-69.1%, and 9.3-46.8%, respectively. Conversely, compost augmentation contributed to increased PO_4 release with CYB, C3YB and CY losses being 166-257%, 221-315%, and 292-436%, respectively, relative to the influent concentrations.

Several factors contribute to P release from soils. Compost contains organic matter that can actively decompose, albeit being “stable”. As this OM mineralizes, soluble P can be released into the soil for plant uptake, particularly under pH conditions (8.01-8.23) for CYB, C3YB and CY. Conversely, biochar produced under high temperatures (>400 °C), akin to the one used in this study, facilitates high pore surface area (surface area of B = 329 m^2/g) for P adsorption in the soil (Alkharabsheh et al. 2021; Kaya et al. 2022). Biochar addition also raised the control soil’s pH to 8.39 (Table 4-2), under which conditions the phosphates typically participate in inorganic complexation with secondary minerals (e.g., Ca) in the soil. The outer-sphere complexation of P with cations on the surface of biochar is a potential mechanism that could contribute to P complexation (Shepherd et al. 2017). Also, the Olsen-P of CB was the lowest compared to other amended soils. This dilution effect could be another factor for decreased release of P. The combination of high surface area/porosity, high pH, carbon content and stability offer P retention advantages to the biochar amendment over compost. Therefore, biochar incorporation with compost reduced the P effluent losses from CYB and C3YB soils compared to CY.

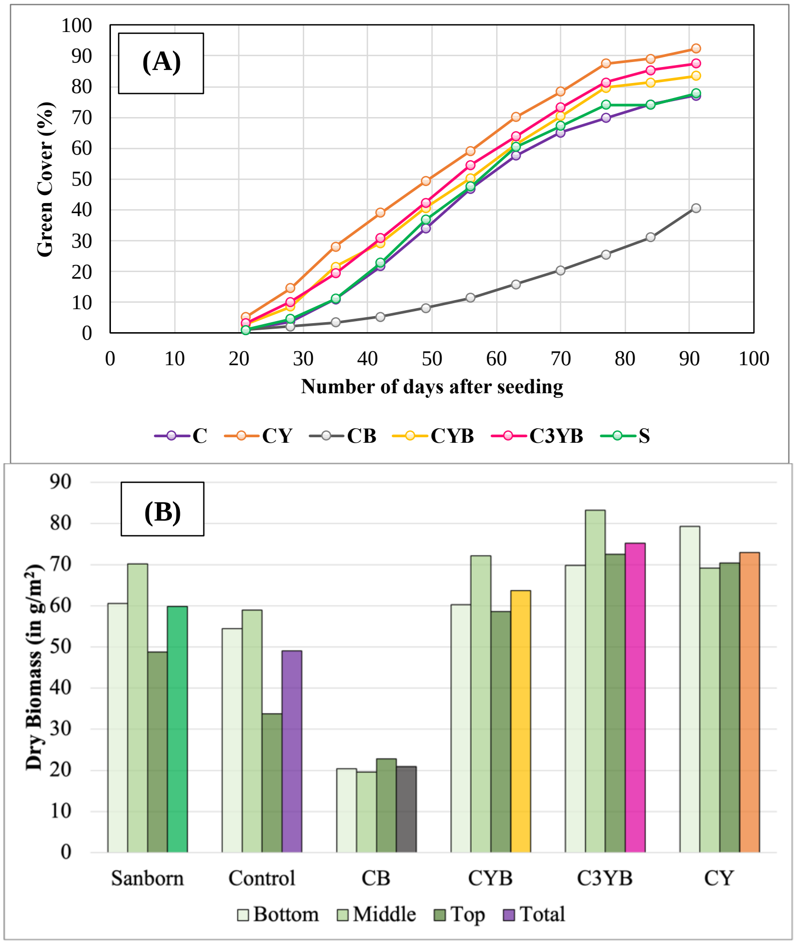
Vegetation Growth

Fig. 4-6A illustrates the weekly progression of vegetation coverage, starting from 21 days after seeding. The sequence of coverage across different soil types was consistently observed as CY>C3YB>CYB>S>C>CB throughout the growth period. CY soil was distinctly superior to others in terms of vegetation coverage, in that it produced more rapid and prominent green cover and recorded a final coverage of 92.3%. And the least effective soil (CB) covered only 40.6% ground at the end. The two unamended soils, C and S, demonstrated comparable performance with overlapping coverage plots and both reaching a final green coverage of ~77%.

As the %GC does not provide detailed insights into sub-surface plant growth, it was necessary to evaluate physical aboveground measurements. The dry biomass was collected at 91 days after seeding from each box. The total biomass yield per surface area was highest in C3YB (75.2 g/m^2), followed by CY (72.9 g/m^2), CYB (63.7 g/m^2), S (59.8 g/m^2), C (49 g/m^2), CB (20.9 g/m^2) (Fig. 4-6B). This shows that the coverage alone does not determine the density of the plant matter that is growing in the soils. The application of yard waste compost as a nutrient-rich amendment notably enhanced the overall plant yield. Conversely, the inclusion of biochar alone into the control soil severely stunted plant growth, corroborating the observations made in vegetation coverage. Besides, plant biomass, the leaf area of black-eyed Susans was also measured because of their strong prevalence in the soils. The trends remained consistent where the addition of compost led to an increase in leaf area in the CY soil, while CB due to the biochar amendment had the lowest impact (Fig. 4-6C). The findings from the pot study (CHAPTER 3) also revealed similar highlights that the leaf area of BES was reduced when biochar was incorporated into the soil; in contrast, the addition of composts promoted leaf expansion. The compost content in the soil mixtures (CYB and C3YB) had a more marked influence on vegetation compared to biochar. CYB and C3YB resulted in a 30% and 53% increase in biomass, respectively, while 12% and 43% expansion of the leaf area index of the BES plant, respectively, compared to the control soil.

To understand potential disparities in plant growth along the soil profile, biomass and BES leaf area were collected and analyzed from three 0.61-m sections: top, middle, and bottom. The biomass production in the top layer of the soil bed was lower compared to the middle and/or bottom layers across all the soils. In the C soil, the bottom and middle sections produced 61% and 75% more biomass than the top section, respectively. In Sanborn, the biomass was 44% higher in the middle and 24% higher in the bottom than the top section. Such variations in plant biomass along the soil sections were significantly reduced and (if) existed at lower than 23% in the amended soils. The leaf area of the BES plants was also greater in the bottom and middle sections compared to the top across all soils. In agronomy, the PAN (NO_3^- + NH_4^+) in the soils is often correlated to the growth and development of plants. Data comparing PAN levels pre- and post- growth of the study soils indicated that soils amended with compost (CYB, C3YB and CY) had the highest PAN, while the one with biochar alone (CB) had the least. Notably, post-growth measurements also showed an increased accumulation of nitrogen at the lower end of the soil bed, which can be attributed to the mobility of nitrogen in the soil profiles with each rainfall application.

While PAN is essential for plant development, soil moisture content will aid the nutrient's availability. The moisture data from the sensors (Fig. 6-13) showed that the soils C and S had lower moisture contents compared to the amended soils, particularly when biochar was present. Among these soils, the moisture content ranges (in increasing order) were Sanborn, 0.15-0.3 m^3/m^3; Control, 0.15-0.32 m^3/m^3; CY, 0.15-0.4 m^3/m^3; C3YB, 0.23-0.45 m^3/m^3; CYB, 0.2-0.5 m^3/m^3; CB, 0.3-0.57 m^3/m^3. Furthermore, moisture content varied along the slope, with the top section being drier across all soils ($p < 0.05$). These findings suggest that the organic amendments, especially when combined, can effectively retain and supply sustained nutrient and water needs for plants. This is particularly beneficial for uniform plant growth on steep terrains like a 2:1 slope.



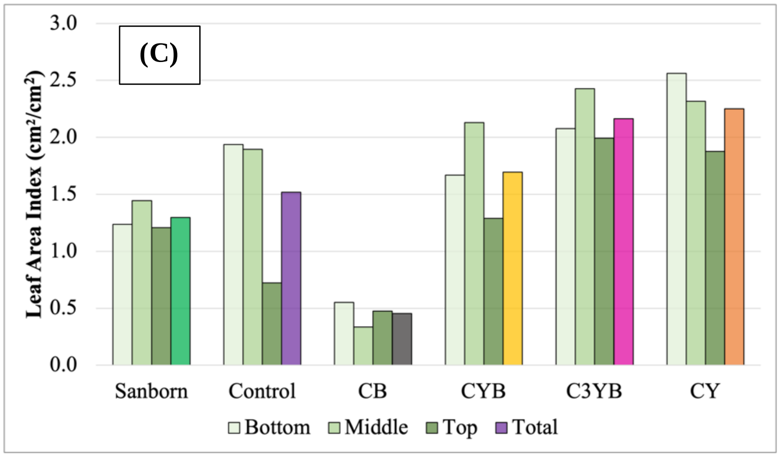


Fig. 4-6. (A) Weekly vegetation coverage (as % Green) **(B)** End-of-the-study dry plant biomass (in grams) **(C)** End-of-study leaf area index of the BES plants (in cm^2/cm^2)

The uptake of nitrogen plays a pivotal role in plant morphology. The CY soil demonstrated the highest average tissue N concentrations, while the CB soil showed the lowest, with the mixtures (CYB and C3YB) falling in between (Fig. 4-7). The higher is the plant available nitrogen (Table 4-1) in the soil, the greater was the plant nitrogen concentrations (Fig. 4-7). In the context of nitrogen, a key factor that influences the plant growth and soil fertility is the C:N ratio. When comparing the amended soils, the results indicated that the compost reduced the soil C:N ratio, subsequently lowering the plant C:N ratio (Table 4-3). The opposite was also true for biochar, where its addition increased the C:N ratios of both the soil and plant. This ratio in living or senesced plant material is essential for maintaining a balanced C:N ratio for the soil microbes as plant litter gets incorporated back into the soils as OM.

Table 4-3. Soil (pre-growth) and plant C:N ratios

Soils	Soil C:N	Plant C:N
Sanborn	14.2	15.8
Control	15.5	15.8
CB	52.4	19.5
CYB	23	16.3
C3YB	17.8	14.7
CY	13.3	13.8

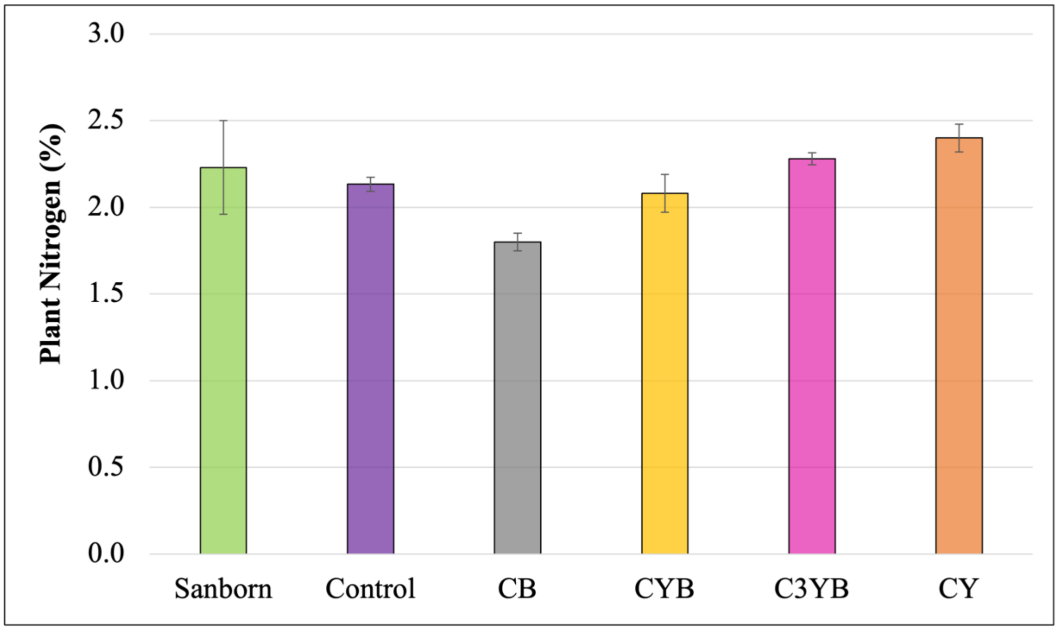


Fig. 4-7. End-of-study plant tissue analysis for nitrogen

Phosphorus is another vital macronutrient that determines plant development, particularly related to roots, flowering, and providing disease resistance. Fig. 4-8 illustrates the tissue P concentrations. While biochar application reduced N levels in soil, water, and plants, its addition increased P in the soils. The tissue P results show that sole additions of biochar (CB) and compost (CY), both increased the phosphorus in plants by 24% and 26%, respectively, compared to the control soil. More notably, the plants in the biochar-compost mixed soils showed even higher tissue P levels than those in CY or CB soils alone. The sequence of Olsen-P (a measure of plant-available P) was observed as CB (10.24±0.16 mg-P/kg) < CYB (24.9±0.74 mg-P/kg) < C3YB (31.6±2.12 mg-P/kg) < CY (36.8±2.76 mg-P/kg). Despite CB having the lowest concentrations of Olsen-P among the amended soils, the biochar amendment might have enhanced phosphorus availability for plant uptake, potentially due to improved moisture retention in the soil (Fig. 6-13).

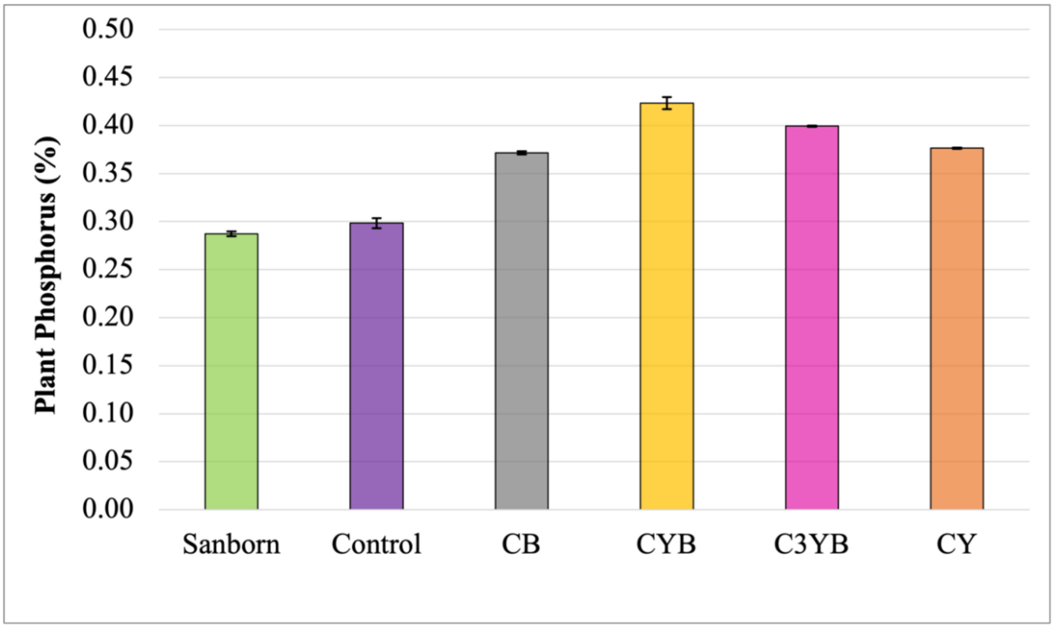


Fig. 4-8. End-of-study plant tissue analysis for phosphorus

The adsorption curves for phosphorus (amount of P adsorbed vs P in the equilibrium solution) are displayed in Fig. 4-9. The control soil (C) adsorbed greater amount of P compared to the CB soil for all P loadings (0 - 5 mg-P/L). In fact, CB favored P desorption at 0.75 mg-P/L and the adsorption was more prominent only at higher loadings of P (2.5 and 5 mg-P/L). Xu et al. (2014) also observed that P desorption increased when biochar was added to soil. In the mesocosm experiment, the PO_4-P in the effluent was consistently lower than the influent P (~0.3 mg-P/L) across all rainfall applications. This discrepancy in P behavior pattern between the experiments can be attributed to the inherent differences in experimental conditions. The adsorption experiment, being a small-scale lab test, involves measurements taken under equilibrium conditions. In contrast, the mesocosm experiment encompasses soil-water dynamics that are affected by applied rainfall intensity, percolation, presence of vegetation, all of which occurred under the state of non-equilibrium. Given these variances, a difference in sorption pattern of P is to be expected. Nonetheless, the results from the adsorption test can still provide a conservative estimate of what might potentially occur in the field.

Biochar alone was also subjected to the adsorption test to understand the intrinsic properties of this amendment in P capture/release, separate from soil interactions. Two additional P loadings (10 and 25 mg-P/L) were also added in the biochar experiment, as previous research highlighted greater sorption power of biochar at higher P loadings (Xu et al. 2014). The data indicate that under P loadings < 5 mg-P/L, desorption occurred for the biochar, which suggests this amendment can liberate P, particularly at lower concentrations. Xu et al. (2014) also noted P adsorption at high P loadings and desorption at lower concentrations, although their high concentrations were > 40 mg-P/L. This can further explain the utilization of P by the plants when the biochar amendment is added to the soil. The combination of soil and biochar (CB) helped retain the excess P, possibly due to interactions with calcium minerals in the alkaline soils (as per Shepherd et al. (2017) findings) as also inferred from effluent water quality data. Contrastingly, the meta-analysis from Glaser and Lehr (2019) noted that P availability from biochar in alkaline soils is not significant and of wood-derived biochar might not be an effective as a P fertilizer. Overall, while wood-based biochar (combined with soil) improved water quality in this study, it was also successful in fertilizing the soils with P for plants uptake.

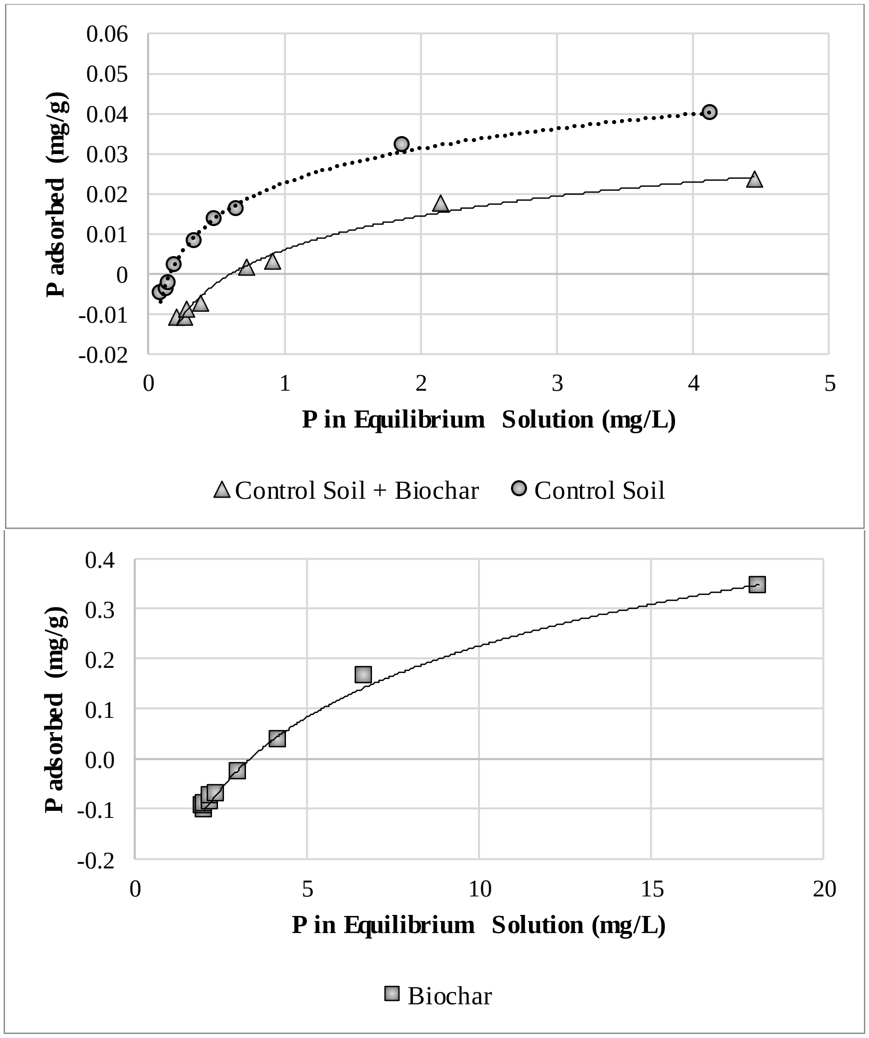


Fig. 4-9 Phosphorus Adsorption Curves of C, CB and biochar media. The P loadings for the C and CB soils ranged between 0 and 5 mg-P/L, and for biochar the chosen range was 0 – 25 mg-P/L. The pH of the experiment was kept constant at 8.8 and measurements were determined at equilibrium conditions after 24 hours.

Conclusions and Environmental Implications

This study tested the effectiveness of concurrently amending soils with compost and biochar in a greenhouse mesocosm scale experiment. In terms of vegetation establishment, singular biochar addition to the control soil (CB) stunted plant growth (reduced biomass, leaf area and coverage). The addition of compost alone to the control soil (CY) resulted in better plant growth than other study media. Compost and biochar mixtures also promoted plant growth, with improvements more pronounced with higher compost proportions in the soil. Plant growth across the soil bed indicated that amended soils also yielded more uniform coverage than unamended control soil.

The suspended solids (a measure for erosion) in the soil effluents were dramatically reduced when the amendments were added to the control soil. Water quality data revealed that the biochar amended soil (CB) caused lower N export to the effluent compared to other study soils. Conversely, the compost amendment caused greater release of N from the soils. An inverse relationship between effluent N and soil C:N ratio was observed. Compost incorporation caused greater phosphorus loss in the effluent, with higher P export correlating to increased compost content in the soil. However, the influent (tap water) P was effectively retained by CB soil throughout the study period. Biochar showed potential for desorbing P based on adsorption test results. However, this released phosphorus was subsequently bound within the soil matrix, limiting its transfer into water.

Soil OM may be increased by 5%-10% by weight basis when using leaf-based composts. This amount should be adjusted based on the slope of the ground, with lower rates of compost application recommended for steeper slopes. Utilize biochar with compost to improve soil OM, especially on steep terrains. This combination is noted for its dual advantages: it not only contributes to healthier vegetative growth but also plays a significant role in enhancing water quality. This blend has also been found to improve soil moisture content, which is particularly beneficial for plant growth and soil health. While this study tested two different compost-biochar mixtures in large-scale mesocosms, more of such mixture should be further examined to develop specific nutrient management plans.

Acknowledgments

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FooD Systems) that was awarded to the University of Maryland School of Public Health by the National Science Foundation National Research Traineeship Program, Grant number 1828910.

CHAPTER 5. CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH

The pressing need to establish vegetation quickly along road/highway shoulders has prompted the use of organic and recycled amendments to improve soil fertility. In this research, various organic materials were incorporated into urban topsoils to increase the organic matter content and assessing their impact not only on soil and vegetation, but also water quality. Commonly used materials, wood mulch, leaf compost and biosolids were investigated with respect to nutrient water quality in a mesocosm-scale greenhouse tub study. A separate pot study was conducted, specifically focusing on plant establishment and growth patterns as affected by the addition of composts (derived yard-waste, food-waste and turkey litter) and a wood-based biochar. Since leaching/runoff is a concern with nutrient rich amendments (as witnessed in the tub study) and poor vegetation with that of wood-based biochar (based on the pot study observations), a third study evaluated the efficacy of compost-biochar mixtures as a best management practice to improve plant growth and water quality in a scaled up mesocosm study. The findings from this study identified OAs that are well-suited for fostering rapid and healthy vegetation growth while minimizing adverse environmental consequences.

Experiment 1 (Chapter 2): Nutrient Transport, Strength, and Hydraulic Characteristics of Topsoils amended with Compost, Mulch and Biosolids

Conclusions: Nutrient water quality data indicated that introducing biosolids led to increased nitrogen release through soil infiltration, while mulch effectively retained nitrogen within the soils. The speciation analysis showed that nitrate was the predominant nitrogen form under steady-state conditions. Leaf compost also enhanced nitrogen release compared to the control soil but exhibited a gradual decrease, reaching 4.5 mg-N/L by the end of the study. The nitrogen release patterns were inversely related to the carbon-to-nitrogen (C:N) ratios of the soils; lower ratios (<15:1) led to nitrogen leaching, while higher ratios (>15:1) reduced it. When mulch and biosolids were added to topsoils, phosphorus retention (effluent P < influent P) increased, due to soil minerals such as iron (Fe) and calcium (Ca) in these materials. In contrast, leaf compost initially retained phosphorus but exhibited a breakthrough mechanism when tap water phosphorus was continuously introduced to the soils. Additionally, the organic amendments improved soil hydraulic properties and had a minimal (but positive) impact on shear properties.

Recommendations: To address nitrogen concerns, biosolids should be incorporated into roadway topsoil based on agronomic nitrogen requirements, not to raise soil organic matter. Mulch has a high C:N ratio, which therefore effectively retained nitrogen in the soil and reduced N release, but caused plant nutrient deficiencies (Morash 2024). Use of fertilizers alongside mulch is recommended for better OM and nutrient supply, balancing vegetation goals and water quality. Leaf compost should be considered as a preferable OM improvement option with lower water quality issues, due to sustained reduction in nitrogen release and phosphorus retention in soils. Overall, when aiming to increase the organic matter by 1-2%, leaf compost is the recommended soil amendment for optimizing the soil-water-vegetation relationship.

Experiment 2 (Chapter 3): Optimizing Native Vegetation Establishment in Urban Soils: Assessing the Impacts of Organic Amendments on Specific Growth Parameters

Conclusions: This research revealed that the turkey-litter compost had a detrimental impact on plant growth due to excessive salinity and ammonium toxicity when used to increase organic matter in soils. Although biochar initially improved plant coverage, it resulted in nutrient deficiencies and negatively affected plant biomass, morphology, and nitrogen uptake. Consequently, plant coverage alone did not provide a comprehensive picture of overall plant health. Furthermore, the type of compost and soil influenced nitrogen uptake and leaf area, with F and T amendments showing higher nitrogen uptake in some soils. A linear correlation was established between plant N and leaf area index, which suggests that nitrogen uptake is crucial to provide plant its structure.

Recommendations: Considering the study's findings, it is advisable to restrict the use of concentrated manure-based composts for improving roadside soil organic matter. Such composts should be applied according to recommended nitrogen agronomic rates to support proper nutrient management practices. Alternatively, it is recommended to supplement wood-based biochar products with nutrient fertilizers to ensure sustained and healthy vegetation support. While delayed plant growth was observed in soils amended with food waste and yard waste composts, they have the potential to release plant nutrients over an extended period while maintaining healthy vegetation. Previous research has underscored water quality issues with yard and food waste composts, so an overapplication (more than 5-6% increase in OM) of these composts is not advisable. These findings can inform the choice of organic amendments based on specific soil characteristics and desired plant outcomes.

Experiment 3 (Chapter 4): Performance of Compost-Biochar Amended Soils with respect to Vegetation, Water Quality, and Hydraulic Properties

Conclusions: The 12-week long growth study demonstrated that vegetation (growth rate and establishment) was most positively influenced when yard-waste compost was the sole amendment used to increase the OM of the control soil. Conversely, amending with biochar deterred plant growth, resulting in a significant decrease (-51.7% to -36.5% green coverage) compared to other media. The compost-biochar mixtures also yielded positive impacts on vegetation against the control soil. Regarding water quality, biochar demonstrated higher nitrogen and phosphorus retention capabilities compared to the other soils studied. The addition of yard-waste compost did not significantly affect nitrogen quality but mobilized a significant portion of orthophosphate along with organic P into the runoff. The addition of biochar to compost reduced the P levels but continued to export greater P than typical stormwater concentrations. Nitrogen concentrations reduced across all soils after 30.5 cm of rainfall, while P concentrations remained consistent throughout the experiment.

Recommendations: This study lays the foundation for the possible utilization of compost and biochar mixtures in topsoil remediation to mitigate erosion and enhance stormwater quality. It suggests the need to revise regulations to encourage the widespread adoption of these symbiotic organic materials to enhance soil health along shoulders. The incorporation of such blends introduces a novel approach for field projects, allowing for the responsible use of compost-based products alongside materials like biochar. Further field assessments are necessary to examine the effectiveness of these mixtures in real-world scenarios.

Future directions:

1. A more in-depth exploration of nitrogen transformations by conducting in-situ measurements of gaseous nitrogen species, thereby filling a critical gap in this study, can provide valuable insights into the nitrogen budget.
2. Characterizing organic matter in amended soils by identifying its moieties or functional groups that participate in specific soil nutrient dynamics, in response to the amendments.
3. It is important to note that the greenhouse mesocosms in this research did not fully replicate field conditions, especially those related to antecedent dry periods. Therefore, investigating the effects of wetting and drying cycles on these mixtures, particularly concerning nitrogen transformations (noting the birch effect), is essential.

4. Additionally, developing sustainable engineered materials (e.g., compost-biochar mixtures) that support plant yield while safeguarding the environment.

CHAPTER 6. APPENDIX

Appendix A (Chapter 2)

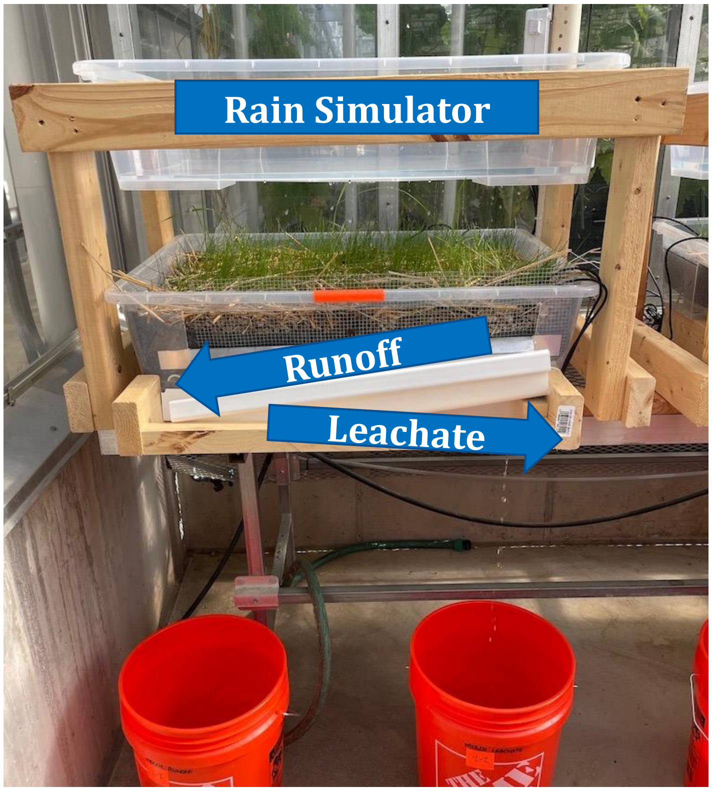


Fig. 6-1. An example of a tub system used in the growth/leachate experiments conducted at the UMD Greenhouse Facility (Morash 2024)

Table 6-1. Water quality analysis methods, instruments, and lowest standards

Soil Property	Units	Method	Instrument	Lowest Method Detection Limit
pH	-	EPA method 9040C	VWR symphony B40PCID	2
EC	µmho/cm	EPA method 9050A	VWR symphony B40PCID	0.001µmho/cm
TOC	mg/L	680°C combustion catalytic oxidation method	Shimadzu SSM-5000A Total Organic Carbon/Total Nitrogen Analyzer	0.1 mg-C/L

TN	mg/L	720°C thermal decomposition - chemiluminescence method	Shimadzu SSM-5000A Total Organic Carbon/Total Nitrogen Analyzer	0.1 mg-N/L
NO_3-N	mg/L	Ion chromatographic method	Dionex ICS-1100 ion chromatograph (ASRS 4 mm suppressor and Dionex IonPac AS22 column)	0.1 mg-N/L
NO_2-N and	mg/L	Sulfanilamide method (4500-NO_2)	SEAL AQ300 Discrete Nutrient Analyzer	0.05 mg-N/L
NH_4-N	mg/L	Salicylate method (4500-NH_4)	SEAL AQ300 Discrete Nutrient Analyzer	0.01 mg-N/L
OP	mg/L	Ascorbic Acid method (4500-P)	SEAL AQ300 Discrete Nutrient Analyzer	0.01 mg-P/L
TDP and TP	mg/L	Digestion using EPA persulfate method 365.1 followed by	SEAL AQ300 Discrete Nutrient Analyzer	0.01 mg-P/L

Table 6-2. Soil analysis methods, instruments, and lowest standards

Soil Property	Units	Method	Instrument	Lowest Method Detection Limit
pH	-	ASTM D4972	VWR symphony B40PCID	2
EC	µmho/cm	FAO method	VWR symphony B40PCID	0.001µmho/cm
OM content (LOI at 455 °C)	%	AASHTO T267	Thermonlyne™ Muffle Furnaces	-
TC	%	Combustion at 950 °C (infrared detection)	LECO CN628 analyzer, LECO corporation	0.0001%
TN	%	Combustion at 950 °C (thermal conductivity)	LECO CN628 analyzer, LECO corporation	0.0001%
P, Al, Fe, Mg, Ca	mg/kg	Mehlich-3 extraction	Shimadzu Model ICPE-9820	1 mg/kg

Table 6-3. Chemical Properties of the Tub Study 1 and Tub Study 2 Soils from Pre- and Post- Vegetation Growth

Tub Study 1	**CUT1**		**MAT1**		**LAT1**		**BAT1**	
Measurement	*Pre-*	*Post-*	*Pre-*	*Post-*	*Pre-*	*Post-*	*Pre-*	*Post-*
OM (%)	7.2	6.4	6.32	5.86	6.03	6.25	5.76	6.56
EC (mmho/cm)	0.59	0.3	1.37	0.79	0.8	0.47	2.16	0.94
pH (1:1)	6.7	6.87	6.57	6.93	6.78	7.01	6.19	5.2
C (ppm)	31980	29774	30215	24402	29000	31049	26662	29257
N (ppm)	1242	1687	1628	1501	1958	1875	3956	3661
C:N ratio	25:1	18:1	19:1	16:1	15:1	17:1	7:1	8:1
P (ppm)	30	23	16	18	23	23	111	127
Ca (ppm)	1834	1818	2171	1843	1993	2145	1311	1341
Mg (ppm)	153	143	126	111	378	386	181	200
Fe (ppm)	507	512	339	441	406	429	850	704
Al (ppm)	875	742	498	622	726	772	1023	902

Tub Study 2	**CUT2**		**MAT2**		**LAT2**		**BAT2**	
Measurement	*Pre-*	*Post-*	*Pre-*	*Post-*	*Pre-*	*Post-*	*Pre-*	*Post-*
OM (%)	4.34	3.99	6.86	5.41	5.92	5.06	5.64	5.1
EC (mmho/cm)	0.3	0.28	0.28	0.37	0.59	0.34	1.89	0.57
pH (1:1)	7.21	7.55	7.31	7.52	7.18	7.55	6.79	7.21
C (ppm)	15522	15923	29631	25360	25901	22414	22868	23411
N (ppm)	1386	1394	1460	1664	2223	1919	2935	2553
C:N ratio	11:1	11:1	20:1	15:1	12:1	12:1	8:1	9:1
NH_4-N (ppm)	1.15	2.38	0.88	2.2	0.9	1.88	87.8	2.95
NO_3-N (ppm)	35.1	0.58	28.3	0.85	81.2	0.3	137	8.4
P (ppm)	16	16	17	17	27	29	90	54
Ca (ppm)	2162	1965	2412	2242	2483	2303	2681	2141
Mg (ppm)	143	127	153	161	206	188	196	159
Fe (ppm)	394	351	438	451	533	398	577	452
Al (ppm)	786	755	832	882	984	830	861	834

Particle Size Distribution: Three TS1 soils fall in the USDA soil textural category of sandy loam, with LAT1 classified as a silt loam owing to its fines content (Table 6-4). Addition of organic amendments to TS2 control soil (CUT2), produced a slight increase in the silt fraction. All TS2 soils were thus classified as silt loam. Additionally, the variability in TS2 soils for fines or gravel content was minimal (within 4%) given that the same control soil was used.

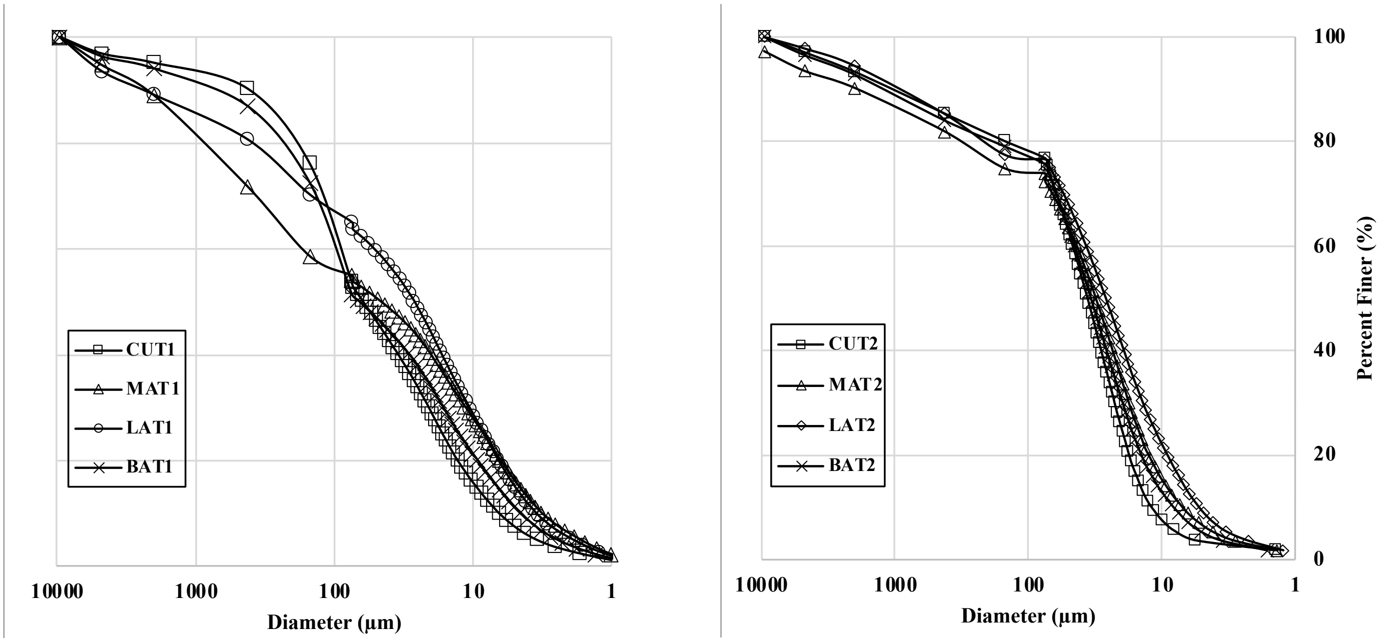


Fig. 6-2. Grain Size Distribution of the tub study soils (TS1 and TS2)

Table 6-4. USDA soil classification of the tub study soils (TS1 and TS2)

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

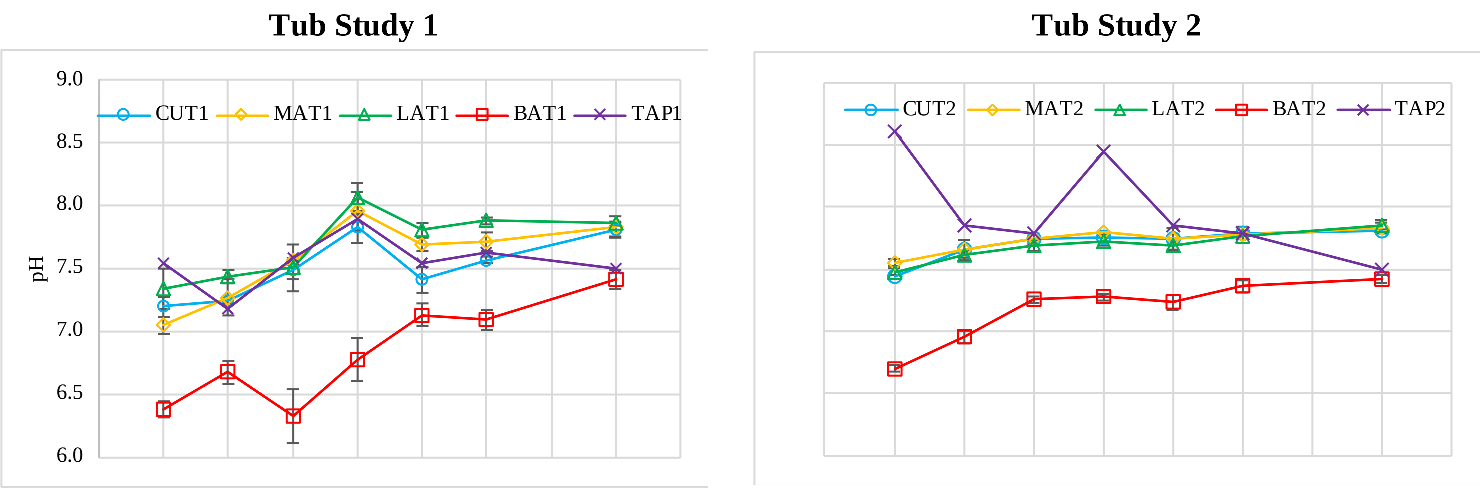
Proctor Test: Table 6-5 shows the compaction characteristics of TS1 and TS2 soils. Soil organic matter plays an important role in the maximum dry density ($\rho_{d,\,max}$) and moisture content (w_{opt}). This effect was noted with the TS1 soils, where the amended soils (MAT1, LAT1, BAT1) showed lower $\rho_{d,\,max}$ when compared to that of the unamended soil (CUT1). This trend was repeated in the TS2 soils, where the addition of mulch, leaf compost, and biosolids to the control soil (CUT2) lowered the maximum dry densities.

Table 6-5. Compaction properties of the tub study soils (TS1 and TS2)

Property	**Tub Study 1 Soils**				**Tub Study 2 Soils**			
	CUT1	*MAT1*	*LAT1*	*BAT1*	*CUT2*	*MAT2*	*LAT2*	*BAT2*
Maximum Dry Density ($\rho_{d,\,max}$) (kg/m^3)	1698	1595	1637	1576	1631	1544	1583	1583
Optimum Water Content (w_{opt}) (%)	16	18	15.5	19.5	18	20	16.5	18

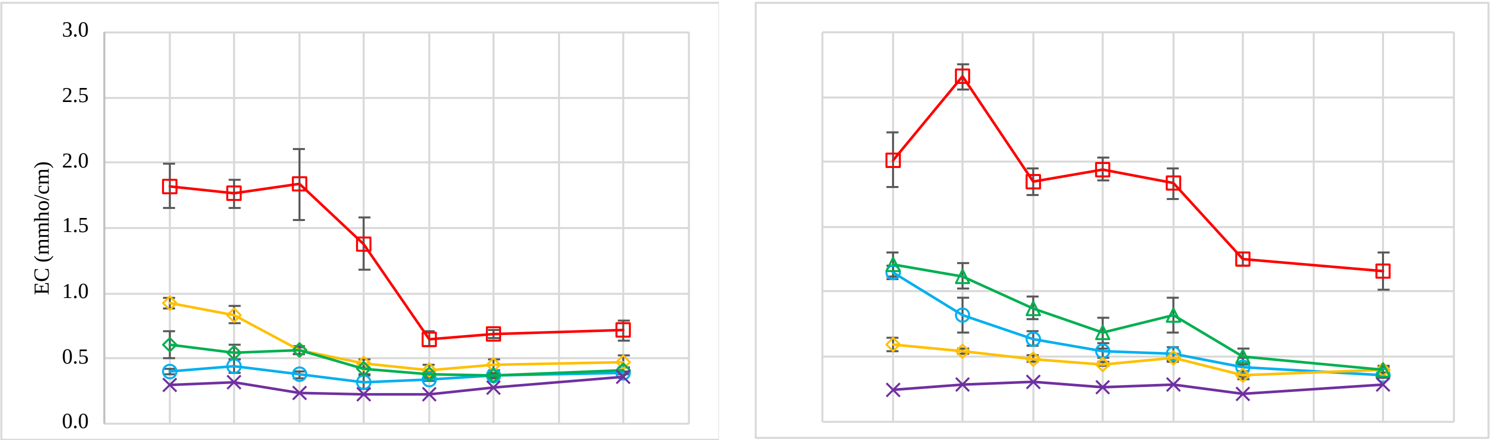
General Water Quality Parameters: Fig. 6-3 shows the trends of the four-replicate average pH, EC, and TOC for each treatment in the collected leachate samples. The leachate pH of BAT1 and BAT2 was lower than other treatments across rain events in the respective tub studies. This is in agreement with the soil pH of BAT treatments being the lowest compared to CUT, MAT and LAT (Table 6-3). Toribio and Romanyà (2006) made similar observations where the pH of basic soils decreased with application of sewage sludges. Leachate pH of all TS1 soils from the first and last SREs were CUT1 (7.2±0.08 and 7.42±0.05), MAT1 (7.05±0.07 and 7.64±0.08), LAT1 (7.34±0.16 and 7.79±0.02), and BAT1 (6.38±0.06 and 6.92±0.07). In TS2, the trend of increase in leachate pH was also observed with the greatest pH difference of 0.7 units in the BAT2 leachate, while the pH of CUT2, MAT2 and LAT2 only increased by <0.4 pH units, regardless of the fluctuations noticed in the influent tap water pH. Changes in pH can be attributed to plant uptake of nitrate and ammonium. Soil acidity is reduced as the plant biomass increases because plants release organic carboxyl ions (which increases soil pH over time) as they take up various anions (Lea-Cox et al. 1996; Marschner 1995). This suggests an increase in pH with each rain application as a result of the observed vegetation establishment (Morash 2024).

A noted decline in leachate EC, followed by steady concentrations was observed in most treatments (Fig. 6-3c and d). This trend was less pronounced in CUT1, LAT1 and MAT2 soils, given that their initial soil EC was lower compared to other treatments (Table 6-3). TS2 studies showed that leaf compost and biosolid amendments increased the EC of the control soil and hence in the leachate too, while mulch reduced EC. Because of the high initial soil soluble salts content (Table 6-3), BAT treatments showed higher EC values overall (up to 2 times), especially in the early SREs, compared to CUT, MAT and LAT. The presence of soluble ions or background electrolytes such as sulfate, chloride, and sodium in biosolids cause an increase in soil EC (Pinto et al. 2018), and one of the effective strategies for reducing the salt content is through soil leaching (FAO 1988; Huffert et al. 2021). This effect was shown in both studies, where EC concentrations were reduced by subsequent simulated rainfall events.



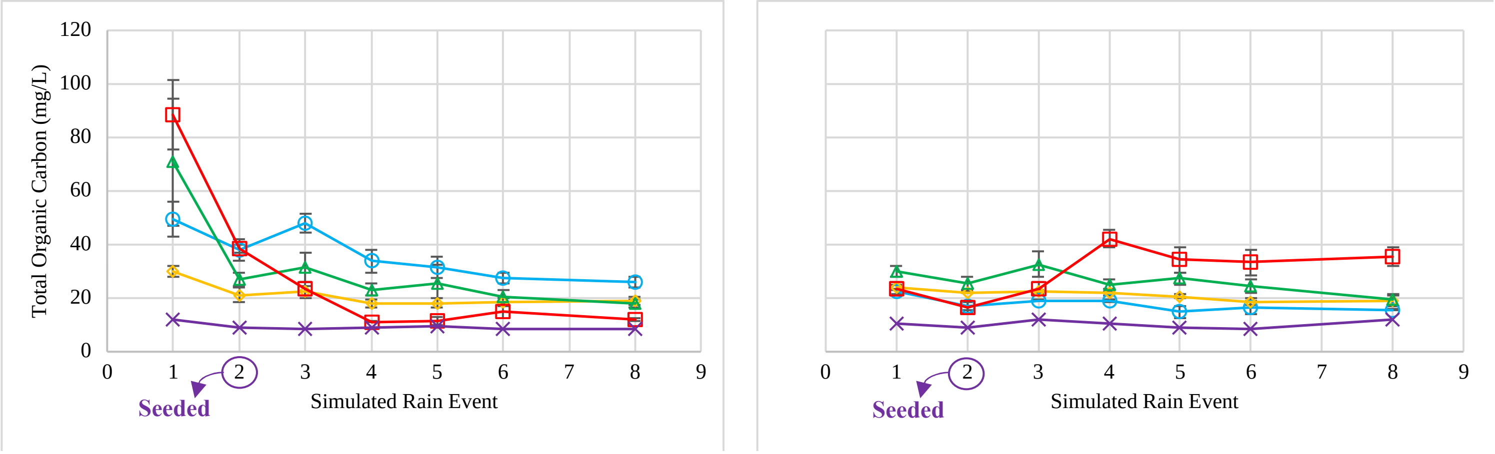
(a) pH

(b) pH



(c) Electrical Conductivity

(d) Electrical Conductivity



(e) Total Organic Carbon

(f) Total Organic Carbon

Fig. 6-3. pH, Electrical Conducitivity (EC) and Total Organic Carbon (TOC) in leachate samples collected from Tub Study 1 (**a, c** and **e**) and Tub Study 2 (**b, d** and **f**) treatments, after eight simulated rainfall events. Error bars indicate standard deviations.

Effluent total organic carbon (TOC) from all tub study soils was greater than the influent concentrations of the tap water (Fig. 6-3e and f). TOC in TS1 leachate samples peaked during SRE 1 followed by a sharp decline in SRE 2; thereafter, TOC gradually decreased and levelled out over time. By the end of the study, TOC from BAT1 declined to concentrations lower than other treatments, even though this treatment exported the highest amounts at the onset of the SREs, when the biosolids amendment was newly incorporated. In TS2, even after the application of organic amendments, the TOC discharges were within the range of 14.9 to 42.3 mg/L across all treatments, compared to the range of 8.43 – 88.7 mg/L in TS1. Additionally, higher TOC leached from amended soils compared to the control soil (CUT2) throughout the rain events.

The steady-state leachate organic carbon concentrations of the treatments were less than 40 mg/L for all soils in this study. This was within the same order of magnitude compared to a bioretention basin incorporated with compost (McPhillips et al. 2018). Chahal et al. (2016) also noted a gradual downward trend of DOC concentrations from compost + sand (40:60 v/v) bioretention mixes over time. O'Keeffe and Akunna (2022) suggested that as nitrification increases in soils, leachable organic C tends to decrease. Although a gradual decrease in organic carbon concentrations were noticed in the TS1 treatments and three of the TS2 treatments (CUT2, MAT2 and LAT2), BAT2 however, performed differently. The BAT2 leachate concentrations rose to its highest mean (42.3 mg/L) after the 4th SRE, later dropped and reached a steady state in successive SREs at 35.6 mg/L (SRE 8), still greater than values for LAT2, MAT2, and CUT2 (15.7 to 19.4 mg/L). This finding corroborates with Fang et al. (2016) where soil amended with sewage sludge leached greater amounts of organic carbon against the reference soil at any given pH between 2 - 13. Additionally, a higher total turf biomass (67.7 g) in BAT2 soils compared to others (Morash 2024) could have influenced the system's TOC export.

Table 6-6. Concentrations and mass transport of TP and TN in leachate and runoff samples of leaf-compost amended topsoil (LAT1) from tub study 1 (TS1)

LAT1 Concentrations (mg/L)

Water Sample	**Rep**	***Total Phosphorus***				***Total Nitrogen***			
		SRE 2	*SRE 5*	*SRE 6*	*SRE 8*	*SRE 2*	*SRE 5*	*SRE 6*	*SRE 8*
Leachate	1	0.28	0.48	**NR**	**NR**	9.38	2.87	**NR**	**NR**
	2	**NR**	0.45	0.54	0.66	**NR**	2.86	2.52	1.82
	3	**NR**	0.73	**NR**	0.48	**NR**	3.28	**NR**	1.85
	4	**NR**	0.50	0.21	0.60	**NR**	3.94	2.26	1.73
Runoff	1	0.40	0.87	**NA**	**NA**	2.58	2.33	**NA**	**NA**
	2	**NA**	1.69	1.91	1.23	**NA**	3.76	3.30	2.51
	3	**NA**	2.00	**NA**	0.73	**NA**	4.33	**NA**	2.06
	4	**NA**	2.01	0.56	0.60	**NA**	6.0	2.39	1.83

LAT1 Mass Transport (mg/m^2)

Water Sample	**Rep**	***Total Phosphorus***				***Total Nitrogen***			
		SRE 2	*SRE 5*	*SRE 6*	*SRE 8*	*SRE 2*	*SRE 5*	*SRE 6*	*SRE 8*
Leachate	1	1.23	1.19	**NR**	**NR**	41.4	7.05	**NR**	**NR**
	2	**NR**	1.25	1.52	2.55	**NR**	8	7.04	6.99
	3	**NR**	2.21	**NR**	1.91	**NR**	9.87	**NR**	7.35
	4	**NR**	1.23	0.49	2.22	**NR**	9.75	5.36	6.42
Runoff	1	2.02	1.28	**NA**	**NA**	13	3.43	**NA**	**NA**
	2	**NA**	1.16	1.06	0.69	**NA**	2.59	1.84	1.40
	3	**NA**	0.90	**NA**	0.81	**NA**	1.95	**NA**	2.29
	4	**NA**	1.17	1.12	0.96	**NA**	3.50	4.82	2.95

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

Appendix B (Chapter 3)

Table 6-7. Soils Source Location (in Minnesota) and their USCS and USDA Soil Classification

Soil	Source Location	%Gravel	%Sand	%Fines	LL (%)	PI (%)	G_S	USCS	USDA
Ortonville	Project site near the intersection of US 12 and 640 Ave	0	45	55	28.8	7.1	2.74	CL	Loam
Sanborn	MnDOT project site “6106-25”	6	66	29	24.4	NA	2.79	SC-SM	Sandy Loam
Clearwater	“Interstate 94 third lane” project	3	74	23	30.3	NA	2.78	SM	Sandy Loam
Glenwood	Project site near the intersection of US 71 and County Road 41	5	67	29	35.4	14.8	2.69	SM	Sandy Loam

CL: Lean clay, SC-SM: Silty clayey sand, SM: Silty sand, LL: Liquid limit (ASTM D 4318), PI: Plasticity index, G_S: Specific Gravity (ASTM D854)

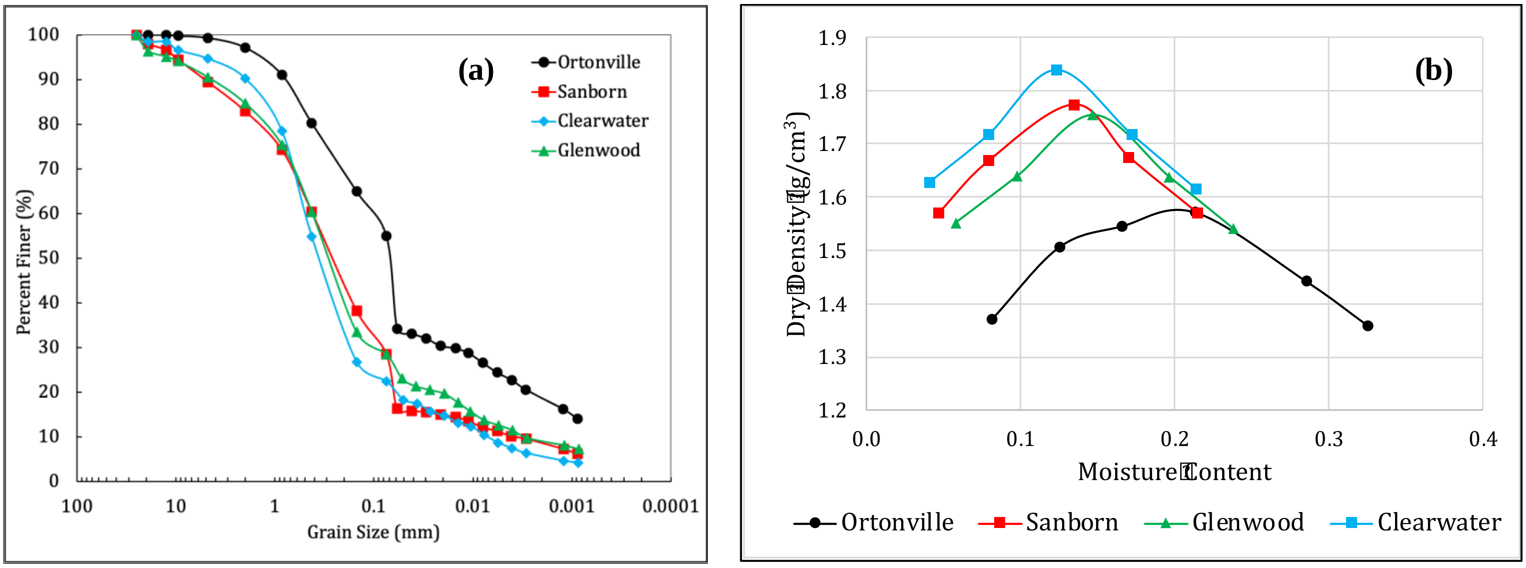


Fig. 6-4. (a) Particle size distribution (PSD) curves and (b) compaction curves of the study soils

Table 6-8. Soil compaction properties along with the corresponding bulk densities and organic matter contents for each soil/OA mixtures

		Subsoil Layer		**Topsoil Layer**	
	Soil/OA	***Maximum Dry Density (g/cm^3)***	***Optimum Water Content (%)***	***Bulk Density (g/cm^3)***	***Organic Matter Content (%)***
Soil	Ortonville	1.58	20	0.84	5.39
	Sanborn	1.77	14	0.97	3.32
	Clearwater	1.84	12	1.04	3.02
	Glenwood	1.75	15	1.02	3.76
OA	Yard Waste	NT	NT	0.78	31.7
	Food Waste	NT	NT	1.02	27.9
	Grade 1	NT	NT	0.6	41.6
	Biochar	NT	NT	0.6	68.9

NT: Not tested

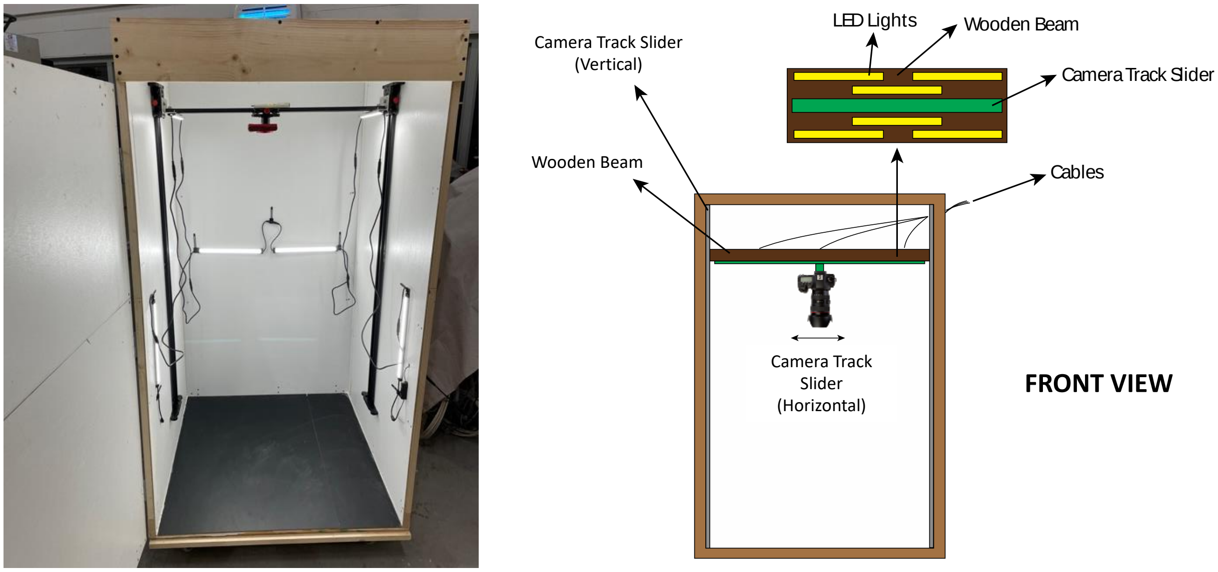


Fig. 6-5. Image station setup

Table 6-9. Soil pH, Electrical Conductivity, and Organic Matter properties

	Glenwood	Sanborn	Clearwater	Ortonville
		pH		
Control	7.45±0.12	7.98±0.02	7.46±0.05	7.75±0.03
YA	7.56±0.03	7.82±0.16	7.6±0.08	7.6±0.09
YB	7.52±0.05	7.77±0.11	7.58±0.01	7.71±0.08
YC	7.62±0.08	7.76±0.1	7.64±0.04	7.77±0.07
FA	7.58±0.04	7.74±0.09	7.73±0.04	7.74±0.05
FB	7.54±0.01	7.72±0.03	7.71±0.03	7.75±0.04
FC	7.5±0.1	7.69±0.07	7.78±0.08	7.77±0.05
TA	7.43±0.09	7.81±0.05	7.82±0.09	7.89±0.03
TB	7.77±0.09	7.94±0.06	7.96±0.09	8.06±0.04
TC	7.8±0.1	7.93±0.06	7.94±0.05	8.01±0.05
BA	7.89±0.08	8.09±0.02	7.99±0.03	7.84±0.03
BB	8.09±0.13	8.2±0.04	8.27±0.03	8.01±0.04
BC	8.22±0.14	8.33±0.06	8.47±0.03	8.24±0.02
		Electrical Conductivity (µS/cm)		
Control	335±37	197±3.5	453±10.7	313±46.4
YA	516±5.3	513±10.3	474±16.7	432±8.6
YB	823±14.9	795±6.7	639±6.6	628±42.1
YC	975±48.7	1039±9.3	839±12.7	852±10
FA	688±9.2	970±11.5	530±28.1	636±52.5
FB	1106±22.7	1351±35.8	736±28.1	1014±36.1
FC	1453±35.3	1626±28.2	956±40.4	1467±18.6

TA	1316±7	1551±11.5	2283±58.6	2560±55.7
TB	2303±65.1	2767±25.2	4343±11.5	5780±52.9
TC	3670±26.5	3890±36.1	5137±37.9	7427±102.1
BA	310±8	216±0.6	312±4	365±44
BB	248±0.6	209±1.2	311±1.2	297±38.7
BC	243±1.5	204±2.1	253±3.5	211±15.6
Organic Matter (%)				
Control	3.76±0.07	3.32±0.04	3.02±0.03	5.39±0.11
YA	5.69±0.37	5.32±0.06	4.26±0.09	8.3±0.22
YB	7.59±0.15	7.46±0.13	5.92±0.1	12.11±0.54
YC	9.82±0.12	9.6±0.09	7.31±0.13	14.44±0.57
FA	5.55±0.38	5.12±0.16	4.23±0.29	7.02±0.34
FB	6.92±0.32	7.36±0.09	6.82±0.17	9.23±0.31
FC	8.45±0.48	9.04±0.2	8.35±0.36	12.1±0.35
TA	5.4±0.06	6.2±0.26	4.95±0.08	7.99±0.35
TB	7.32±0.12	8.05±0.34	6.59±0.17	10.56±0.18
TC	10.01±0.42	11.1±0.11	10.14±0.52	14.22±0.31
BA	5.54±0.12	5.27±0.22	4.89±0.04	8.09±0.16
BB	6.82±0.12	7.6±0.13	5.89±0.09	10.53±0.19
BC	9.76±0.23	9.34±0.12	7.85±0.11	14.15±0.65

Table 6-10. MATLAB code used to fit sigmoid curves to the coverage data and derive the constants

```
clear variables  %Clearing all variables
clc  %Clearing command window

data_matrix = xlsread('coverage_sigmoid.xlsx');  %Reading in data from
Excel file
x = data_matrix(1,:);  %Storing x-values (time in weeks)
% A0 = [0;0;0;0];  %Activate this when regressing with 4 parameters
(vertical shift)
A0 = [0;0;0];  %Activate this when regressing with 3 parameters (no
vertical shift)
C = zeros(156,3);  %Initiating matrix to store parameter values

for i = 2:1:157
y = data_matrix(i,:);  %Storing in y-values (percent coverage)
% sigfunc = @(A, x)(A(1) .* (1 + tanh(A(2).*(x-A(3)))) + A(4));  %Includes
vertical shift
sigfunc = @(A, x) A(1) .* (1 + tanh(A(2).*(x-A(3))));  %No vertical shift
A_fit = nlinfit(x, y, sigfunc, A0);  %Nonlinear regression to find
parameter values
C(i-1,:) = A_fit;  %Parameter values stored in the matrix C
end
```

Table 6-11. Nonlinear regression constants for the growth curves (% green coverage vs growth time)

	K_1 (%GC)	**K_2** (weeks^{-1})	**K_3** (weeks)
O	35.42	0.35	7.44
OTA	17.59	0.69	8.07
OTB	4.92	1.12	9.38
OTC	0.08	6.56	12.89
O	35.42	0.35	7.44
OBA	36.74	0.34	5.79
OBB	35.14	0.37	5.16
OBC	41.01	0.21	6.45
O	35.42	0.35	7.44
OFA	44.84	0.38	9.09
OFB	39.53	0.26	11.49
OFC	33.06	0.31	10.79
O	35.42	0.35	7.44
OYA	32.45	0.40	8.08
OYB	39.81	0.28	8.40
OYC	32.25	0.42	8.21
S	39.25	0.37	6.28
STA	46.70	0.30	11.16
STB	22.81	0.40	11.34
STC	23.64	0.41	12.35
S	39.25	0.37	6.28
SBA	38.68	0.50	6.60
SBB	41.85	0.49	6.96
SBC	34.84	0.26	7.64
S	39.25	0.37	6.28
SFA	35.80	0.45	8.51
SFB	40.86	0.32	9.54
SFC	35.97	0.28	9.38
S	39.25	0.37	6.28
SYA	38.84	0.40	7.53
SYB	46.13	0.42	7.21
SYC	47.69	0.45	6.41

C	42.65	0.37	8.82
CTA	19.77	0.19	13.43
CTB	316.17	0.10	47.46
CTC	0.05	-5.33	2.68
C	42.65	0.37	8.82
CBA	43.45	0.34	6.76
CBB	37.87	0.42	6.94
CBC	43.87	0.31	7.42
C	42.65	0.37	8.82
CFA	38.12	0.35	7.69
CFB	41.42	0.50	7.56
CFC	46.73	0.37	7.84
C	42.65	0.37	8.82
CYA	42.05	0.49	8.53
CYB	39.02	0.38	6.32
CYC	40.15	0.45	7.82
G	40.26	0.39	7.68
GTA	42.40	0.37	6.64
GTB	4519.08	0.13	34.38
GTC	28.22	0.28	10.83
G	40.26	0.39	7.68
GBA	41.66	0.39	6.00
GBB	37.93	0.37	6.63
GBC	38.23	0.29	7.41
G	40.26	0.39	7.68
GFA	34.45	0.36	7.22
GFB	36.97	0.58	7.38
GFC	33.48	0.39	8.59
G	40.26	0.39	7.68
GYA	39.06	0.39	6.78
GYB	39.40	0.27	7.97
GYC	38.22	0.51	6.69

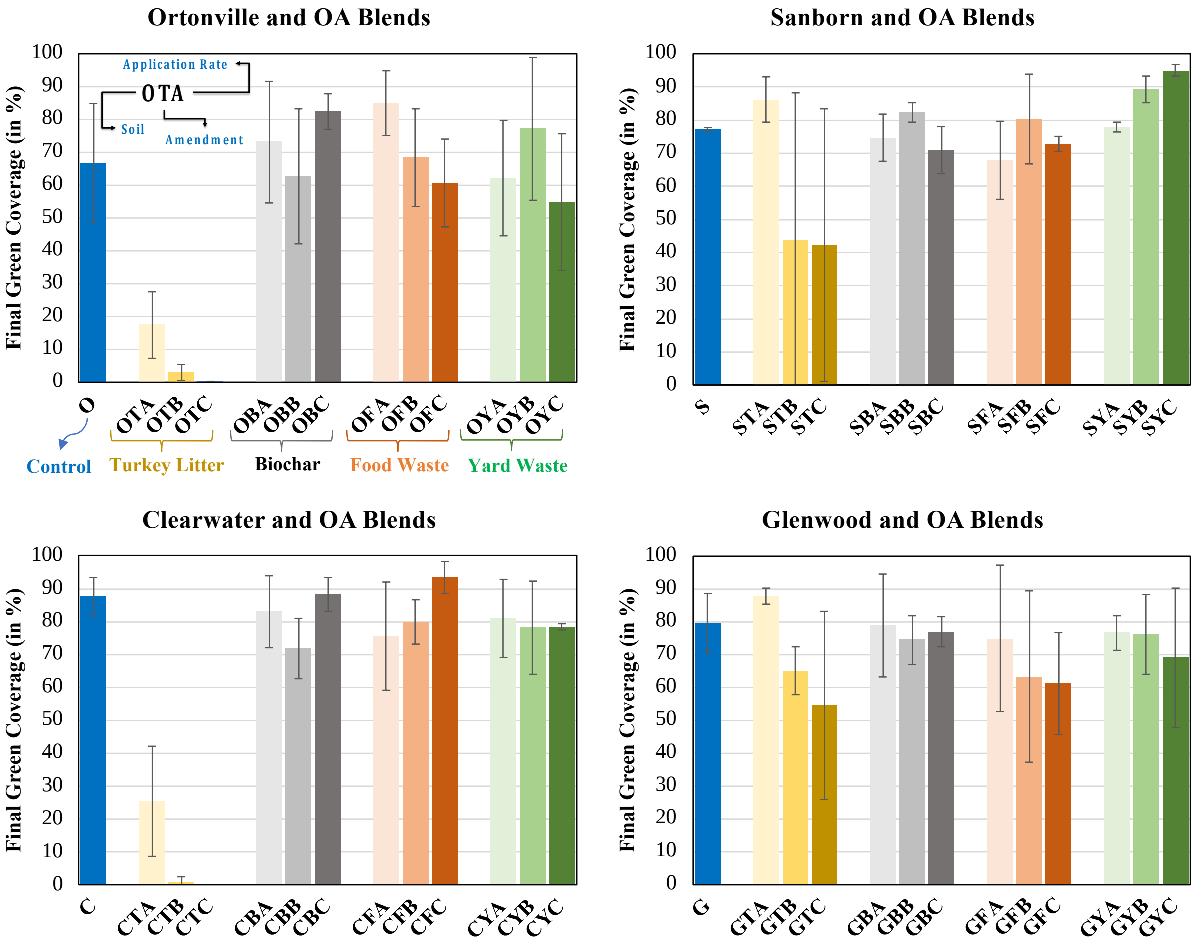


Fig. 6-6. Final green coverage (%) of soil-OA blends

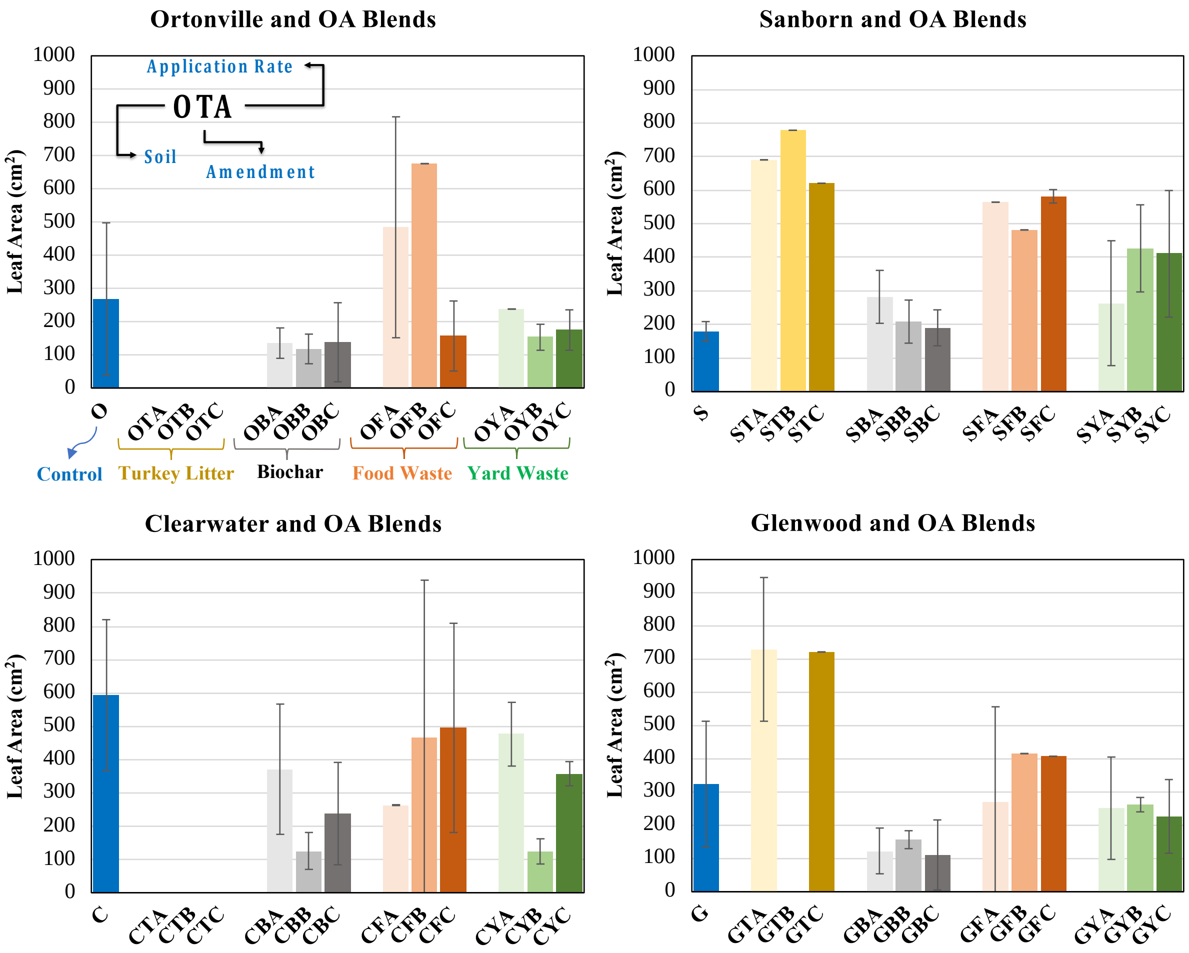


Fig. 6-7. Leaf Area (cm^2) of black-eyed Susan from soil-OA blends

Appendix C (Chapter 4)

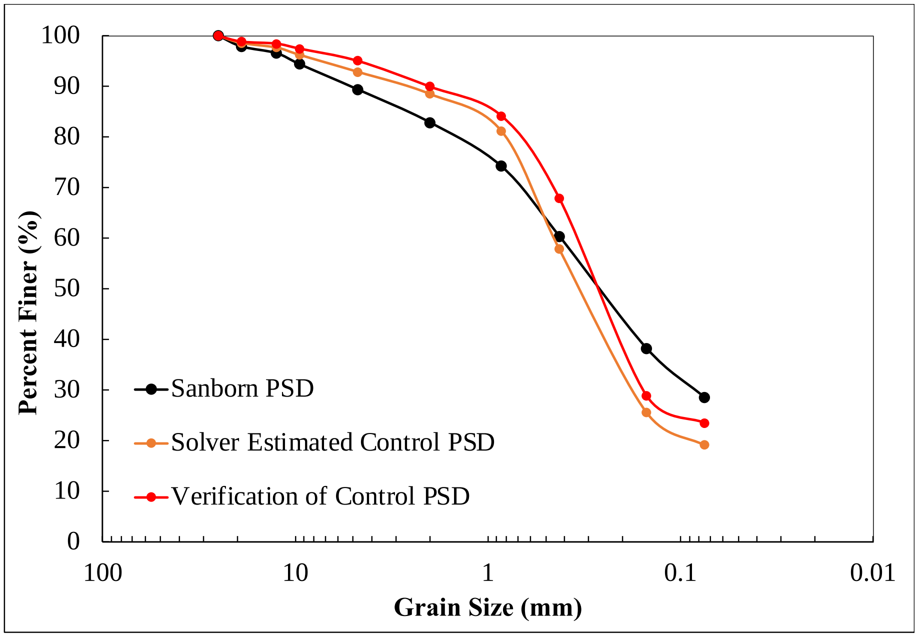


Fig. 6-8. Particle size distribution of Sanborn, excel solver-estimated control mix, and actual control soil.

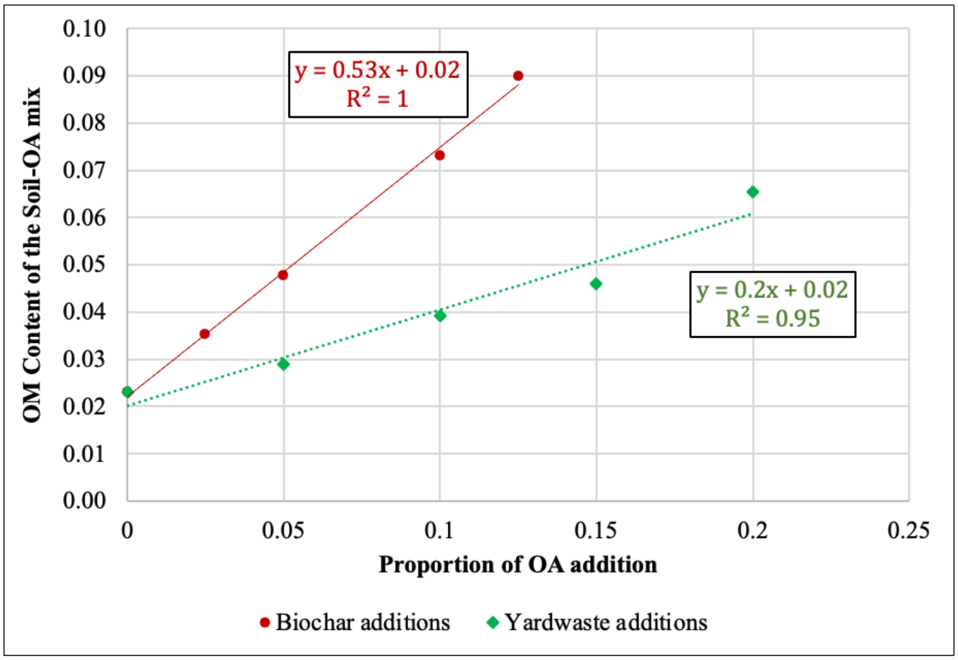


Fig. 6-9. Regression equations used to estimate the amounts of OAs, Sanborn soil, and sands to achieve the target OM content (6.5%) of the soil-OA blends

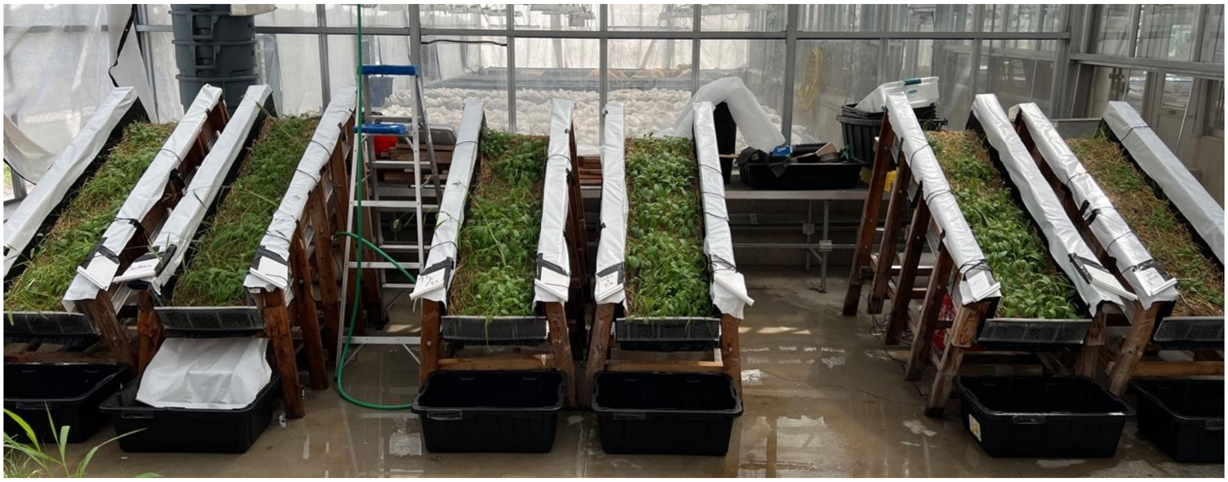


Fig. 6-10. Mesocosm experiment conducted in the UMD greenhouse facility. Effluent samples were collected into the black totes placed in front of each mesocosm.

Table 6-12. Soil analysis methods, instruments, and lowest standards

Soil Property	Units	Method	Instrument	Lowest Method Detection Limit
pH	-	ASTM D4972	VWR symphony B40PCID	2
EC	μmho/cm	FAO method	VWR symphony B40PCID	0.001μmho/cm
OM content (LOI at 455 ℃)	%	AASHTO T267	Thermonlyne™ Muffle Furnaces	-
TC	%	Combustion at 950 ℃ (infrared detection)	LECO CN628 analyzer, LECO corporation	0.0001%
TN	%	Combustion at 950 ℃ (thermal conductivity)	LECO CN628 analyzer, LECO corporation	0.0001%
Olsen P	mg/kg	Olsen extraction	SEAL AQ300 Discrete Nutrient Analyzer	1 mg/kg
Mehlich-3 P	mg/kg	Mehlich-3 extraction	Shimadzu Model ICPE-9820	1 mg/kg

Table 6-13. Water quality analysis methods, instruments, and lowest standards

Soil Property	Units	Method	Instrument	Lowest Method Detection Limit
pH	-	EPA method 9040C	VWR symphony B40PCID	2
EC	μmho/cm	EPA method 9050A	VWR symphony B40PCID	0.001μmho/cm
TOC	mg/L	680°C combustion catalytic oxidation method	Shimadzu SSM-5000A Total Organic Carbon/Total Nitrogen Analyzer	0.1 mg-C/L
TN	mg/L	720°C thermal decomposition - chemiluminescence method	Shimadzu SSM-5000A Total Organic Carbon/Total Nitrogen Analyzer	0.1 mg-N/L
NO_3-N	mg/L	Ion chromatographic method	Dionex ICS-1100 ion chromatograph (ASRS 4 mm suppressor and Dionex IonPac AS22 column)	0.1 mg-N/L
NO_2-N and	mg/L	Sulfanilamide method (4500-NO_2)	SEAL AQ300 Discrete Nutrient Analyzer	0.05 mg-N/L
NH_4-N	mg/L	Salicylate method (4500-NH_4)	SEAL AQ300 Discrete Nutrient Analyzer	0.01 mg-N/L
OP	mg/L	Ascorbic Acid method (4500-P)	SEAL AQ300 Discrete Nutrient Analyzer	0.01 mg-P/L
TDP and TP	mg/L	Digestion using EPA persulfate method 365.1 followed by	SEAL AQ300 Discrete Nutrient Analyzer	0.01 mg-P/L

Table 6-14. Soil Properties post growth conditions (destructive analysis)

Media	**Box Section**	**pH**	**EC (µS/cm)**	**PAN (mg-N/kg)**
Sanborn	Top	8.14 ± 0.02	147 ± 3.00	15.65 ± 2.50
	Middle	8.13 ± 0.01	150 ± 3.80	17.61 ± 0.44
	Bottom	8.13 ± 0.01	159 ± 13.7	17.77 ± 2.04
Control	Top	8.26 ± 0.03	107 ± 3.50	14.21 ± 0.73
	Middle	8.19 ± 0.03	125 ± 11.3	15.05 ± 0.24
	Bottom	8.20 ± 0.03	124 ± 6.00	15.04 ± 0.54
CB	Top	8.38 ± 0.04	139 ± 2.80	12.08 ± 0.16
	Middle	8.33 ± 0.01	143 ± 5.00	11.18 ± 0.14
	Bottom	8.32 ± 0.02	147 ± 2.20	11.69 ± 0.62
CYB	Top	8.32 ± 0.11	159 ± 19.7	17.22 ± 0.63
	Middle	8.24 ± 0.02	184 ± 11.6	19.48 ± 0.59
	Bottom	8.22 ± 0.01	202 ± 12.5	20.94 ± 1.17
C3YB	Top	8.23 ± 0.05	212 ± 12.5	22.74 ± 0.37
	Middle	8.21 ± 0.10	207 ± 7.10	26.02 ± 2.55
	Bottom	8.18 ± 0.05	211 ± 9.10	26.59 ± 1.15
CY	Top	8.22 ± 0.01	208 ± 6.20	25.04 ± 1.23
	Middle	8.13 ± 0.05	218 ± 6.90	27.54 ± 3.28
	Bottom	8.10 ± 0.05	240 ± 24.7	33.50 ± 2.13

All values are denoted as mean ± standard deviation for three representative soil samples collected from each section of the mesocosm

(A) Original Image (B) Cropped Image (C) %GC Analyzed Image

Fig. 6-11. Image processing steps followed for %GC analysis in the mesocosms

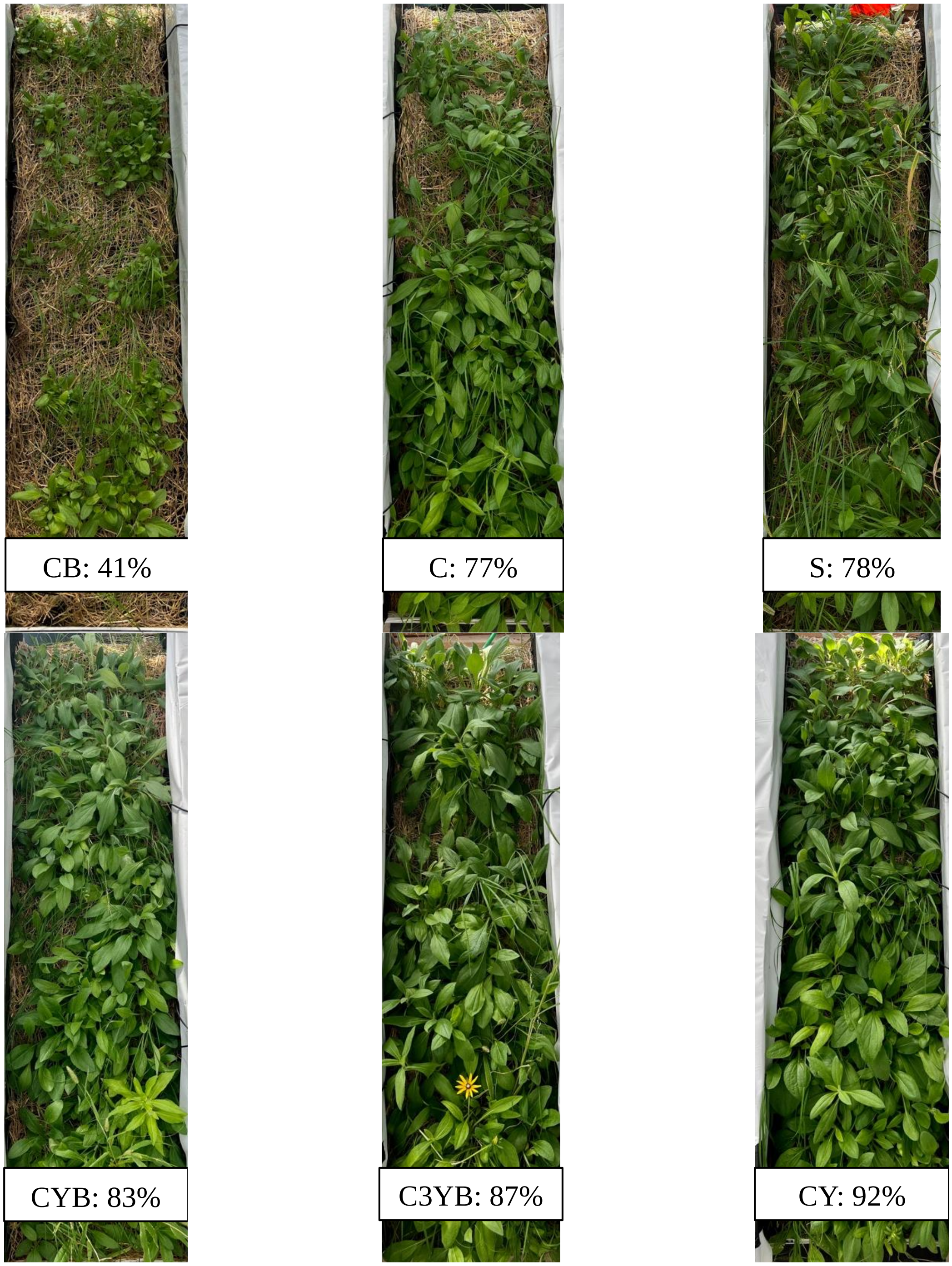


Fig. 6-12. Final vegetation coverage in the soils. Pictures of the soil types are arranged in increasing order of %GC.

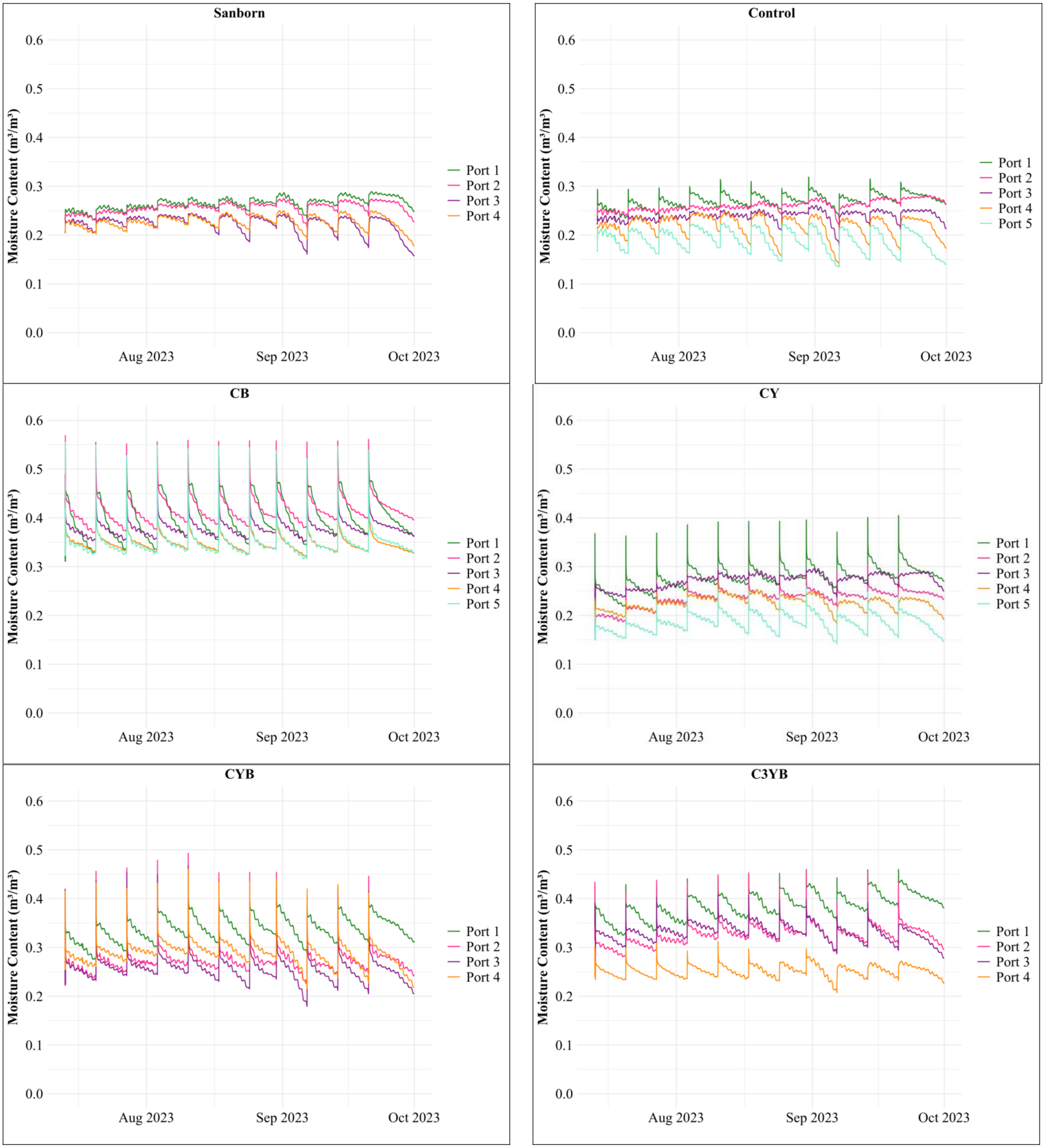


Fig. 6-13. Changes in soil moisture contents (TEROS 12 sensors data) during the experiment starting from July 13, 2023 (week 2). The pulses in moisture mark the rainfall events. The ports are arranged along the soil bed, with port 1 at the bottom and port 5 at the top.

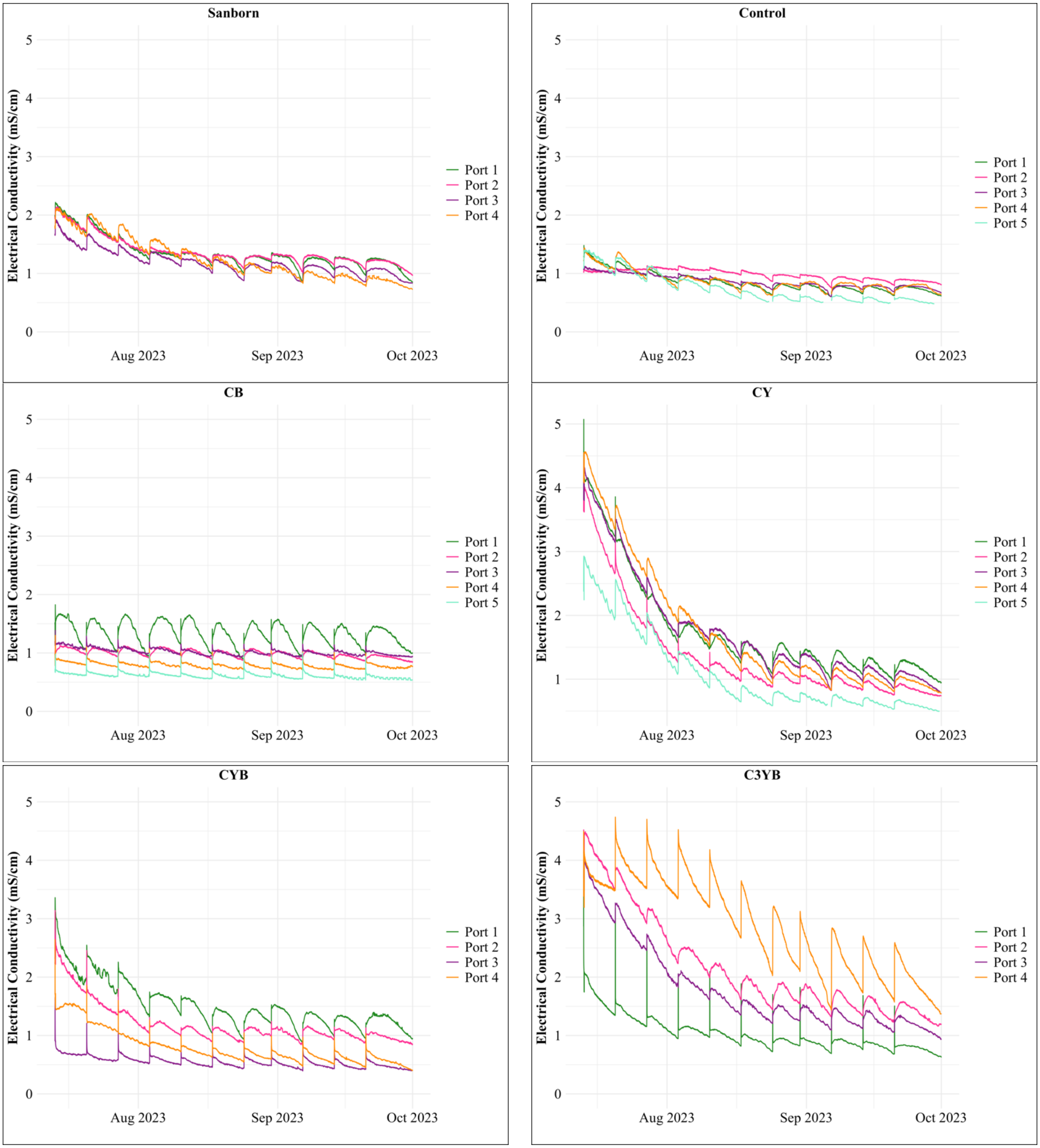


Fig. 6-14. Changes in soil electrical conductivity (TEROS 12 sensors data) during the experiment starting from July 13, 2023 (week 2). The pulses in EC mark the rainfall events. The ports are arranged along the soil bed, with port 1 at the bottom and port 5 at the top.

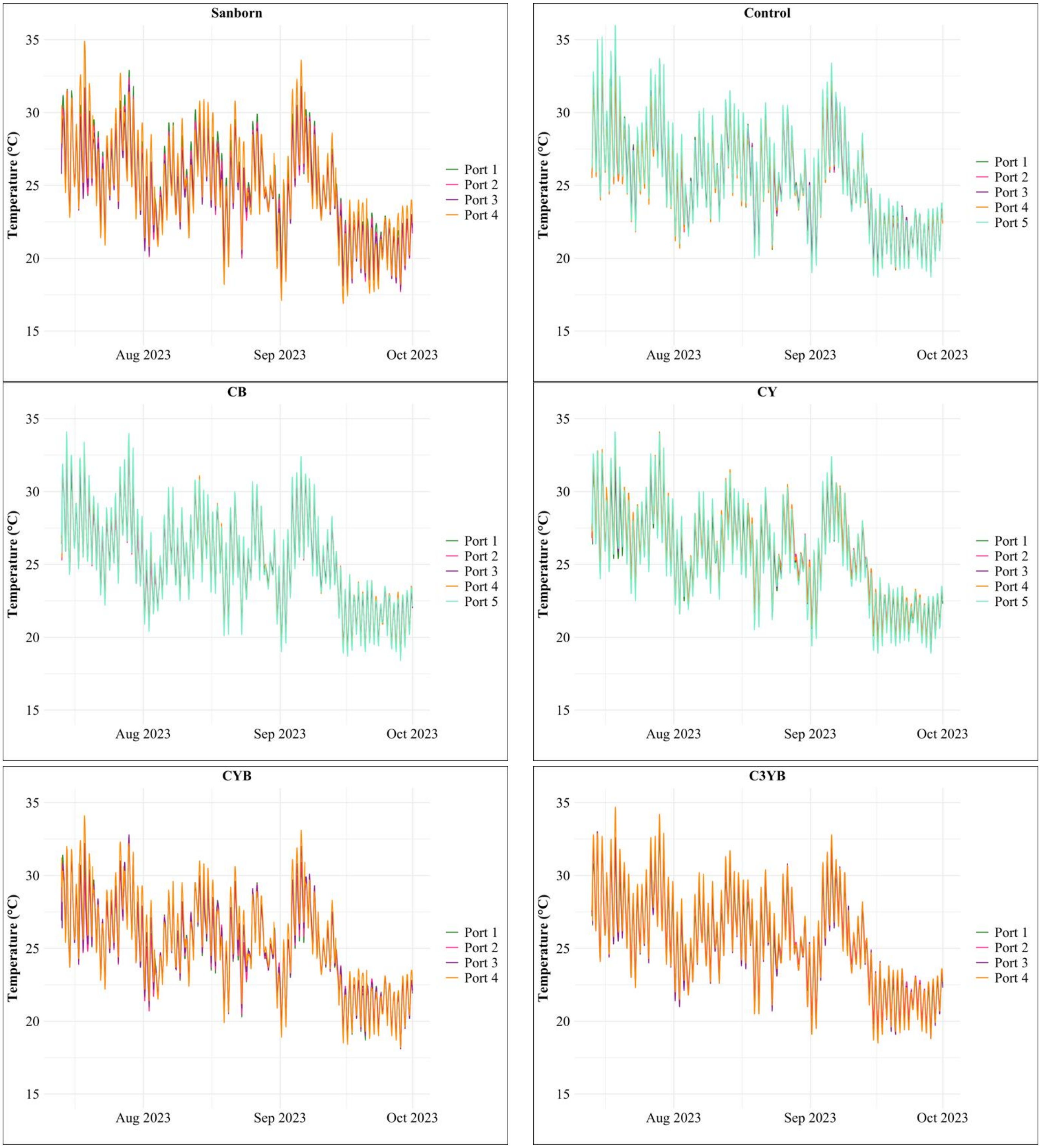
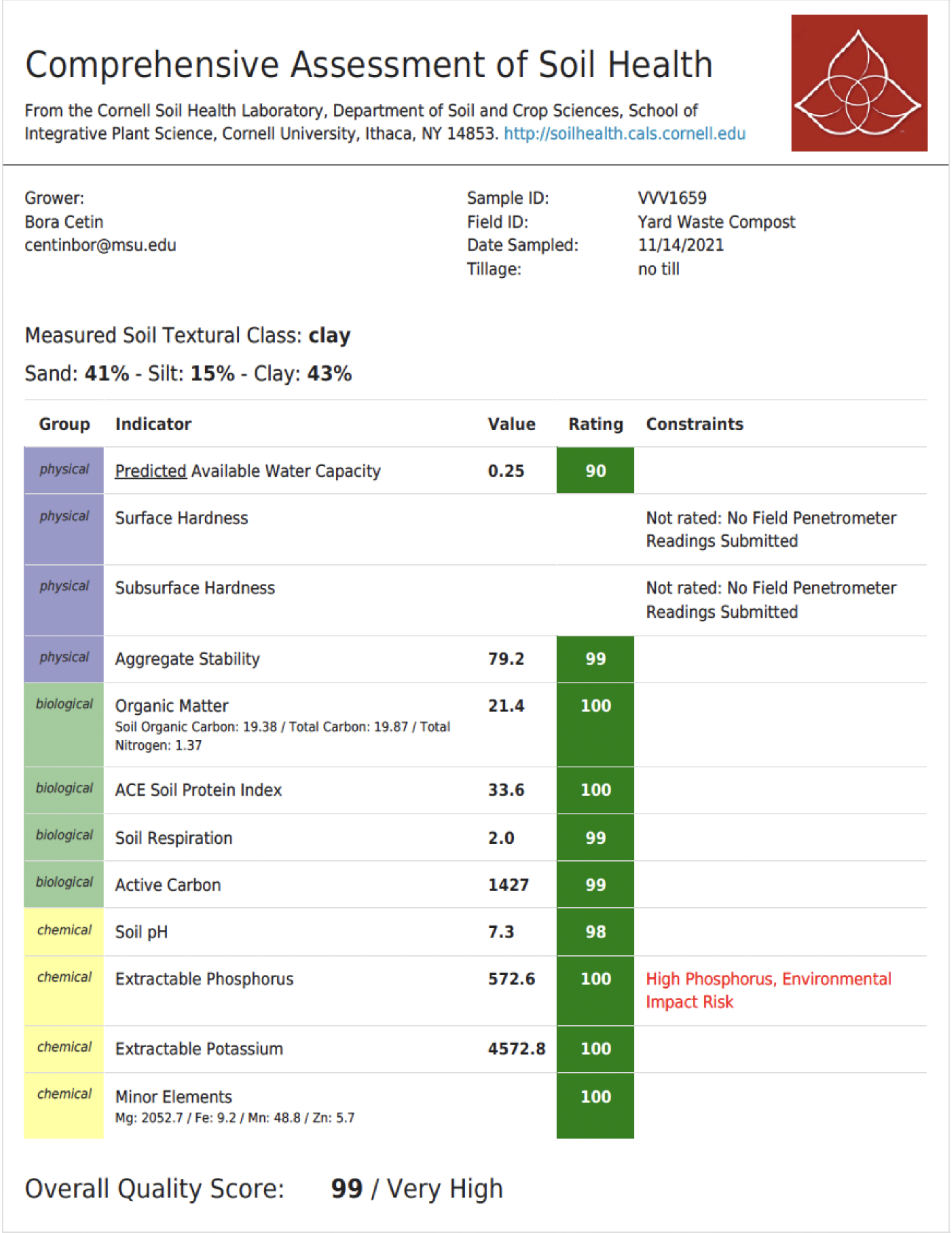


Fig. 6-15. Changes in soil temperature (TEROS 12 sensors data) during the experiment starting from July 13, 2023 (week 2). The ports are arranged along the soil bed, with port 1 at the bottom and port 5 at the top.



Comprehensive Assessment of Soil Health

From the Cornell Soil Health Laboratory, Department of Soil and Crop Sciences, School of Integrative Plant Science, Cornell University, Ithaca, NY 14853. http://soilhealth.cals.cornell.edu

Grower:
Bora Cetin
centinbor@msu.edu

Sample ID: VVV1659
Field ID: Yard Waste Compost
Date Sampled: 11/14/2021
Tillage: no till

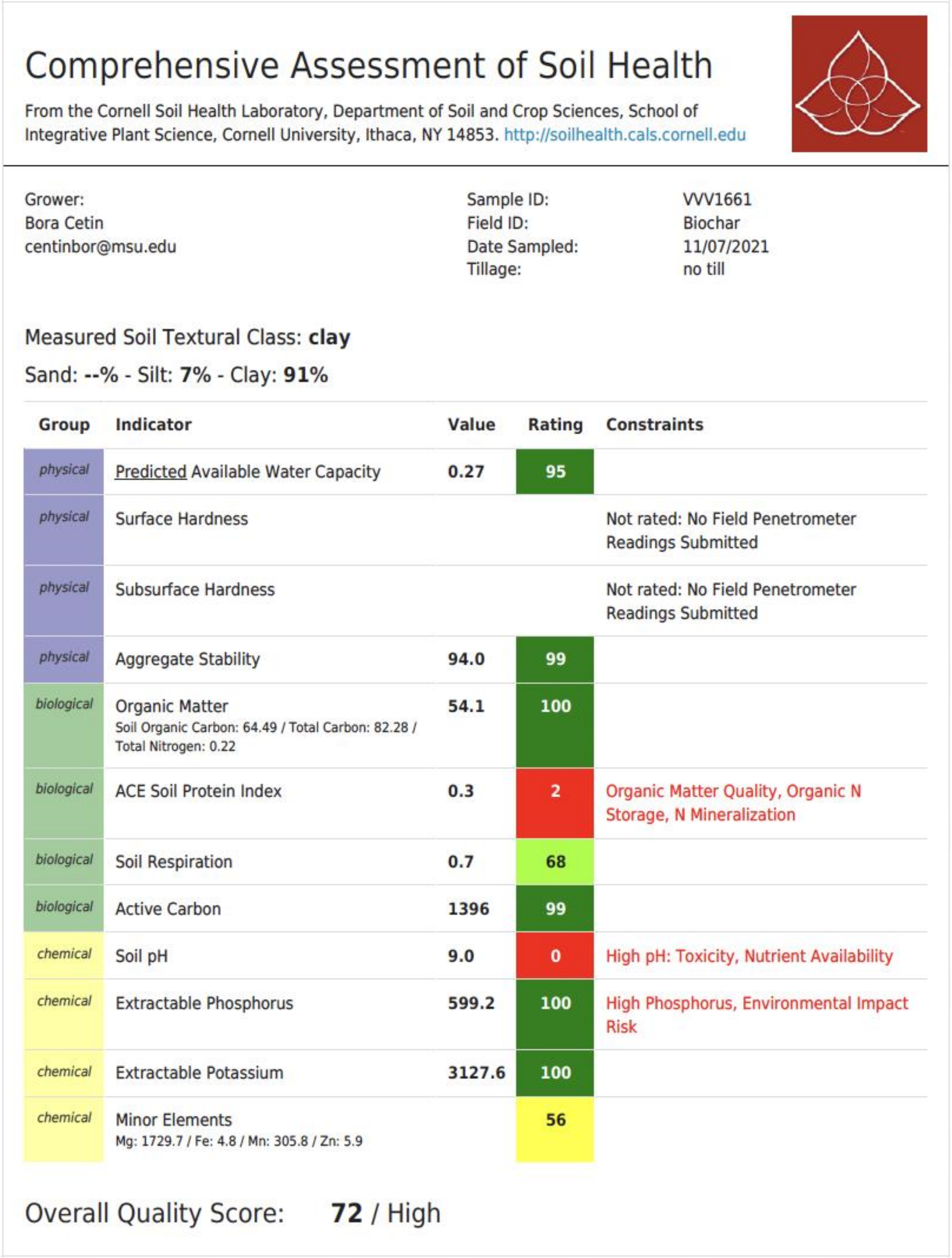
Measured Soil Textural Class: **clay**

Sand: **41%** - Silt: **15%** - Clay: **43%**

Group	Indicator	Value	Rating	Constraints
physical	Predicted Available Water Capacity	0.25	90	
physical	Surface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Subsurface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Aggregate Stability	79.2	99	
biological	Organic Matter Soil Organic Carbon: 19.38 / Total Carbon: 19.87 / Total Nitrogen: 1.37	21.4	100	
biological	ACE Soil Protein Index	33.6	100	
biological	Soil Respiration	2.0	99	
biological	Active Carbon	1427	99	
chemical	Soil pH	7.3	98	
chemical	Extractable Phosphorus	572.6	100	High Phosphorus, Environmental Impact Risk
chemical	Extractable Potassium	4572.8	100	
chemical	Minor Elements Mg: 2052.7 / Fe: 9.2 / Mn: 48.8 / Zn: 5.7		100	

Overall Quality Score: **99** / Very High

Fig. 6-16. Cornell soil health report of yard-waste compost used in the greenhouse mesocosm study



Comprehensive Assessment of Soil Health

From the Cornell Soil Health Laboratory, Department of Soil and Crop Sciences, School of Integrative Plant Science, Cornell University, Ithaca, NY 14853. http://soilhealth.cals.cornell.edu

Grower:
Bora Cetin
centinbor@msu.edu

Sample ID: VVV1661
Field ID: Biochar
Date Sampled: 11/07/2021
Tillage: no till

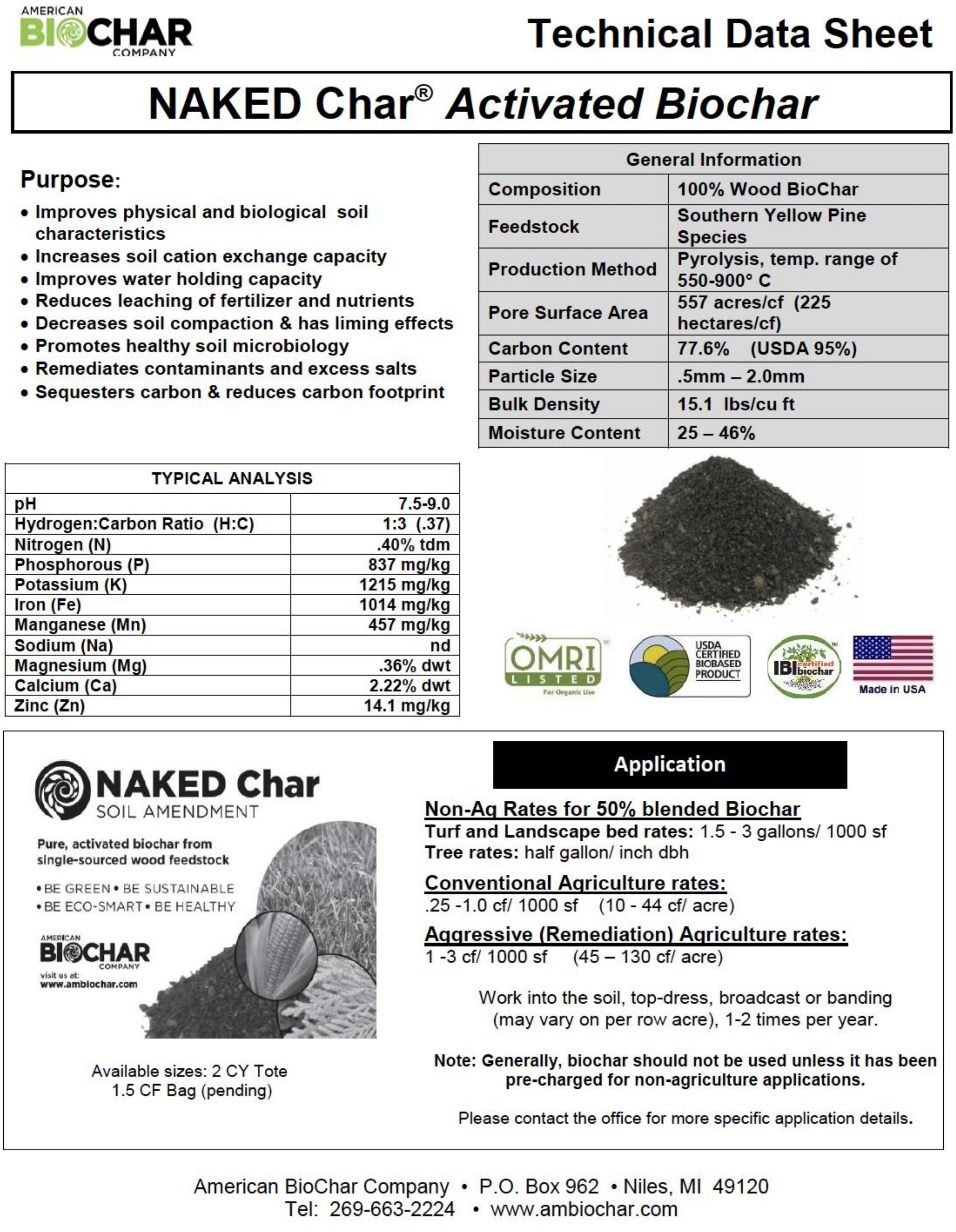
Measured Soil Textural Class: **clay**

Sand: **--%** - Silt: **7%** - Clay: **91%**

Group	Indicator	Value	Rating	Constraints
physical	Predicted Available Water Capacity	**0.27**	**95**	
physical	Surface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Subsurface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Aggregate Stability	**94.0**	**99**	
biological	Organic Matter Soil Organic Carbon: 64.49 / Total Carbon: 82.28 / Total Nitrogen: 0.22	**54.1**	**100**	
biological	ACE Soil Protein Index	**0.3**	**2**	Organic Matter Quality, Organic N Storage, N Mineralization
biological	Soil Respiration	**0.7**	**68**	
biological	Active Carbon	**1396**	**99**	
chemical	Soil pH	**9.0**	**0**	High pH: Toxicity, Nutrient Availability
chemical	Extractable Phosphorus	**599.2**	**100**	High Phosphorus, Environmental Impact Risk
chemical	Extractable Potassium	**3127.6**	**100**	
chemical	Minor Elements Mg: 1729.7 / Fe: 4.8 / Mn: 305.8 / Zn: 5.9		**56**	

Overall Quality Score: **72** / High

Fig. 6-17. Cornell soil health report of biochar used in the greenhouse mesocosm study



AMERICAN BIOCHAR COMPANY

Technical Data Sheet

NAKED Char® *Activated Biochar*

Purpose:

- Improves physical and biological soil characteristics
- Increases soil cation exchange capacity
- Improves water holding capacity
- Reduces leaching of fertilizer and nutrients
- Decreases soil compaction & has liming effects
- Promotes healthy soil microbiology
- Remediates contaminants and excess salts
- Sequesters carbon & reduces carbon footprint

General Information	
Composition	100% Wood BioChar
Feedstock	Southern Yellow Pine Species
Production Method	Pyrolysis, temp. range of 550-900° C
Pore Surface Area	557 acres/cf (225 hectares/cf)
Carbon Content	77.6% (USDA 95%)
Particle Size	.5mm – 2.0mm
Bulk Density	15.1 lbs/cu ft
Moisture Content	25 – 46%

TYPICAL ANALYSIS	
pH	7.5-9.0
Hydrogen:Carbon Ratio (H:C)	1:3 (.37)
Nitrogen (N)	.40% tdm
Phosphorous (P)	837 mg/kg
Potassium (K)	1215 mg/kg
Iron (Fe)	1014 mg/kg
Manganese (Mn)	457 mg/kg
Sodium (Na)	nd
Magnesium (Mg)	.36% dwt
Calcium (Ca)	2.22% dwt
Zinc (Zn)	14.1 mg/kg

NAKED Char
SOIL AMENDMENT

Pure, activated biochar from single-sourced wood feedstock

• BE GREEN • BE SUSTAINABLE
• BE ECO-SMART • BE HEALTHY

AMERICAN BIOCHAR COMPANY
visit us at:
www.ambiochar.com

Available sizes: 2 CY Tote
1.5 CF Bag (pending)

Application

Non-Ag Rates for 50% blended Biochar
Turf and Landscape bed rates: 1.5 - 3 gallons/ 1000 sf
Tree rates: half gallon/ inch dbh

Conventional Agriculture rates:
.25 -1.0 cf/ 1000 sf (10 - 44 cf/ acre)

Aggressive (Remediation) Agriculture rates:
1 -3 cf/ 1000 sf (45 – 130 cf/ acre)

Work into the soil, top-dress, broadcast or banding (may vary on per row acre), 1-2 times per year.

Note: Generally, biochar should not be used unless it has been pre-charged for non-agriculture applications.

Please contact the office for more specific application details.

American BioChar Company • P.O. Box 962 • Niles, MI 49120
Tel: 269-663-2224 • www.ambiochar.com

Fig. 6-18. Technical data sheet of biochar received from *American BioChar Company*

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