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Comparison of Compost and Proprietary Soil Amendments for Vegetation Establishment

Bora Cetin, Principal Investigator
Department of Civil and Environmental Engineering
Michigan State University

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Post-construction roadside soils often suffer from compaction, low fertility, and poor structure, challenging vegetation establishment and stormwater management. This study evaluates the effectiveness of organic amendments (OAs) and proprietary amendments as alternatives to traditional methods. The study involves greenhouse experiments (pot and mesocosm) and field experiments to evaluate vegetation growth and water quality across different amendment and soil applications. Results show that compost amendments significantly improve vegetation growth, with yard-waste compost outperforming others. Biochar shows early growth potential but requires nutrient supplementation for sustained performance. Proprietary amendments support rapid vegetation establishment, enhanced root density, and reduced nutrient leaching, with Sustane 4-6-4 exhibiting consistent growth across application rates. The field study validates greenhouse findings and shows increased biomass and root density with compost amendments, while proprietary amendments result in high nutrient retention and runoff quality. This study highlights the potential use of OAs and PAs to reduce erosion and support long-term vegetation growth. The findings provide practical guidelines, benefits and implementation steps for managing roadside soils after construction activities.

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Comparison of Compost and Proprietary Soil Amendments for Vegetation Establishment

Final Report

Prepared by:

Bora Cetin
Oguzhan Saltali
Angela Farina
Department of Civil and Environmental Engineering, Michigan State University

Sai Thejaswini Pamuru,
Department of Civil and Environmental Engineering, Duke University

Haluk Sinan Coban
Wisconsin Department of Transportation

Ahmet H. Aydilek
Allen P. Davis
Department of Civil and Environmental Engineering, University of Maryland

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Office of Research & Innovation
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St. Paul, Minnesota 55155-1899

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List of Abbreviations

MSU: Michigan State University

UMD: University of Maryland

CSHL: Cornell Soil Health Laboratory

OA: Organic Amendments

PA: Proprietary Amendments

Rate A: The lowest Application Rate

Rate B: The Medium Application Rate

Rate C: The Highest Application Rate

Control: Sanborn and sand mixture (mesocosm)

S: Sanborn soil (mesocosm)

CY: Control + Yard-waste Compost (mesocosm)

CB: Control + Biochar (mesocosm)

CYB: Control + 50% Yard-waste Compost+ 50% Biochar (mesocosm)

C3YB: Control + 75% Yard-waste Compost+ 25% Biochar (mesocosm)

CSC: Control + Sustane 4-6-4 at two times manufacturer's recommended rate (mesocosm)

CSB: Control + Sustane 4-6-4 at manufacturer's recommended rate (mesocosm)

CKB: Control + Kickstand Fe at manufacturer's recommended rate (mesocosm)

CCB: Control + Carbogrow 3-0-3 at manufacturer's recommended rate (mesocosm)

YW: Yard-waste Compost

FW: Food-waste Compost

TL: Turkey Litter Compost

B: Wood-based Biochar

Control: Untreated soil without proprietary amendments or organic amendments (Field)

Carbogrow: Carbogrow 3-0-3 Amendment

Sustane: Sustane 4-6-4 Amendment

Kickstand: Kickstand+ Fe Amendment

Biotic: Biotic Soil Amendment

TN: Total Nitrogen

TP: Total Phosphorus

TSS: Total Suspended Solids

EC: Electrical Conductivity

GI: Growth Index

GC: Green Coverage

OM: Organic Matter

Executive Summary

Post-construction roadside soils often exhibit poor quality, compaction, and low fertility, leading to erosion, inadequate stormwater management, and challenges in vegetation establishment. Traditional methods using topsoil and fertilizers are costly and lack standardized guidelines for application. This study evaluates the effectiveness of organic amendments (OAs) and proprietary amendments (PAs) as cost-effective alternatives for improving soil quality, vegetation growth, and water quality, while reducing maintenance costs.

Laboratory testing of soils, compost, and biochar depicted that compost significantly improved soil stability, water retention, and organic content. The material characterization phase showed that soils had low aggregate stability, resulting in increased runoff potential and erosion risks. Incorporating organic matter into these soils enhanced their structural integrity and showed a potential to increase water infiltration. Compost amendments demonstrated high water retention capacity and macronutrient availability, making them highly effective in improving vegetation establishment. Although beneficial in increasing organic matter and water retention, biochar exhibited limited nutrient availability, indicating that it should be combined with compost or another amendment to ensure sustained plant growth and nutrient supply. The proprietary amendments, including Sustane 4-6-4 and Carbogrow 3-0-3, exhibited strong performance due to their nutrient-rich composition and targeted release profiles, providing immediate and long-term support for vegetation growth.

The greenhouse studies highlighted the importance of amendment rates, with higher application rates generally promoting better growth and biomass accumulation. Sustane 4-6-4 and Carbogrow demonstrated better performance across different soil types, achieving rapid green coverage and higher biomass, especially in sandy loam soils. Conversely, biochar was most effective in early growth stages but showed nutrient limitations in later stages, underscoring the need for nutrient supplementation.

Mesocosm studies focused on evaluating amendment performance under controlled rainfall simulations and highlighted the potential water-quality impacts of amendments. Compost amendments increased nutrient leaching, especially phosphorus, requiring strategies to balance growth performance with water-quality protection. Proprietary amendments such as Kickstand DG+Fe effectively minimized nitrogen losses, improving water-quality outcomes. These findings emphasize the importance of amendment selection and application rates to site-specific conditions to achieve optimal performance while protecting water bodies.

Field studies expanded these insights by validating amendment performance under real-world conditions. Plots treated with yard- waste compost showed improvements in biomass and root density, demonstrating their ability to support robust vegetation growth. Proprietary amendments also improved vegetation coverage and biomass, with Sustane 4-6-4 outperforming controls in nitrogen retention and phosphorus management. These results highlighted the applicability of greenhouse findings, supporting the effectiveness of amendments for roadside vegetation establishment.

This research provides an approach to improving post-construction roadside soils. By incorporating organic and proprietary amendments, the Minnesota Department of Transportation (MnDOT) can enhance erosion control,

stormwater management, and vegetation growth. Recommendations include using yard-waste compost at 1-2% soil organic matter (OM) increase to improve biomass and support robust vegetation growth without compromising on water quality. Alternatively, Sustane 4-6-4 or Carbogrow 3-0-3 at higher rates (C) can be applied to promote rapid growth and enhance water quality. Additionally, recommended amendment application rates will help balance vegetation growth with runoff quality, and developing regional guidelines for amendment use will ensure cost-effective implementation. This research supports roadside management practices, offering practical and actionable guidelines for improving soil health and vegetation establishment.

Chapter 1: Introduction

1.1 Project Overview and Objectives

This Minnesota Department of Transportation (MnDOT) project aims to improve vegetation establishment on post-construction roadside embankments by evaluating the effectiveness of organic amendments (OAs) and proprietary amendments (PAs) as alternatives to conventional vegetation establishment methods involving topsoil and fertilizers. Roadside soils are often of poor quality due to construction activities, resulting in compacted soils with limited fertility, prone to erosion and inadequate stormwater management (Bochet and Garcia-Fayos, 2004; Haynes et al., 2013).The project objective is thus to resolve these issues by developing ideal application rates of compost and proprietary products used as soil amendments to promote rapid vegetation growth, enhance soil quality overall, and reduce construction and maintenance costs. Specific objectives of the study include assessing the performance of these amendments through greenhouse, mesocosm, and field studies, examining their effects on soil and vegetation, and creating guidelines for their use in MnDOT roadside applications.

1.2 Importance of Soil Amendments for Roadside Vegetation

Establishing healthy roadside vegetation is critical to stormwater management and erosion control. The degraded condition of roadside vegetation leads to the fact that poor-quality soils left after road construction are deficient in organic matter and nutrients that support vegetation, thereby, making them more susceptible to erosion, with reduced stormwater infiltration and further aggravation of problems due to increased runoff (Bloorchian et al., 2016; Muerdter et al., 2018; US EPA, 2013). Traditional methods of vegetation establishment using topsoil and chemical fertilizers can be costly and create environmental risks such as excessive nutrient leaching (Carpenter et al., 1998; Duran Zuazo and Rodriguez Pleguezuelo, 2008). Soil amendments, including organic (compost and biochar) and proprietary fertilizer-like products, offer an alternative approach by improving soil structure, enhancing nutrient content, and promoting rapid vegetation growth (Faucette et al., 2004; Farrell & Jones, 2009). By integrating soil amendments into roadside soil remediation, MnDOT aims to create solutions that enhance soil quality, facilitate vegetation establishment, and reduce maintenance needs (Kranz et al., 2020).

1.3 Benefits of Organic Amendments and Proprietary Amendments

OAs and PAs have the potential to significantly benefit soil quality and vegetation establishment in post-construction roadside embankments. Organic amendments, such as compost and biochar, are usually derived from organic waste materials and can improve soil structure, organic matter content, and nutrient availability. Compost, in particular, has been shown to increase soil porosity, lower bulk density, and reduce water runoff while improving soil water infiltration and retention, consequently improving the health of vegetation (Landschoot and McNitt, 1994). The compost also supports microbial activity and nutrient cycling, which is an important aspect of plant growth, leading to increased biomass production (Evanylo et al., 2016; Garling and

Boehm, 2001). Another organic soil amendment, biochar, increases the porosity of soils and enhances the availability of nutrients. Its performance depends on the feedstocks used for its preparation and the conditions under which the pyrolysis occurs (Agegnehu et al., 2017; Singh et al., 2010). While biochar can initially enhance soil conditions, its long-term nutrient availability may be limited; however, it has the potential to improve microbial habitat and conditions for microbial nutrient cycling. PAs on the other hand are commercial products designed to address specific soil deficiencies and promote plant growth. Proprietary amendments typically consist of a combination of organic and inorganic elements, including essential nutrients like nitrogen (N), phosphorus (P), and potassium (K), which are crucial for plant health. Proprietary amendments like Sustane and Kickstand promote rapid vegetation establishment and improve plant health in nutrient-deficient soils (Watkins and Trappe, 2017; Linde and Hepner, 2005). These products are formulated to enhance root development, increase above-ground biomass, and improve soil nutrient-holding capacity. In addition, PAs like Kickstand are effective at reducing nitrogen export, thereby minimizing nutrient leaching and contributing to better water quality outcomes (Brown and Gorres, 2011). Overall, both OAs and PAs can provide practical solutions for soil improvement and vegetation establishment. Their use can enhance plant growth, improve soil structure, and reduce erosion, making them valuable additives for roadside vegetation establishment and erosion control.

Chapter 2: Literature Review

2.1 Best Management Practices for Roadside Vegetation Management in Minnesota

A healthy roadside environment provides many benefits, including (1) reduction in soil erosion, maintenance needs, and costs, (2) improved infiltration and water quality, (3) safety for vehicles and travelers, (4) limited accountability of stakeholders, and good public relations. After roadway construction is complete, the soil at construction sites is often highly degraded and compacted. Establishing vegetation may be difficult due to poor soil conditions. Improving the physical and chemical conditions of post-construction soils may facilitate establishment of vegetation cover (USEPA, 2011). An increasingly common approach to increasing vegetation growth potential is the use of compost in conjunction with tillage (Strecker et al., 2015). In addition, several proprietary soil amendments have been successfully used for roadside vegetation establishment and erosion prevention (Watkins and Trappe, 2017).

While these suggested amendments for roadside soil quality restoration pose the potential to be cost-effective and provide better vegetative growth, no guidelines exist to determine the mixing ratios for compost/proprietary amendments and poor soils. Even though past experience indicated success in vegetation establishment, these techniques still need to be evaluated based on native grass seeding, native soil characteristics, and climate conditions (Weiss et al. 2005). Use of compost(s) and proprietary soil amendment(s) can be cost-effective soil quality restoration treatments for improving vegetation establishment on roadsides (Weiss et al. 2005; Olson et al. 2013; Chen et al. 2013; Heitman and McLaughlin 2017). Table 2.1 shows a list of major studies conducted on restoration of roadside soil quality for improving vegetation, focused on (a) use of amendments (e.g., compost, proprietary amendments, and biochar) for topsoil remediation, (b) tilling and reducing compaction of topsoil, and (c) use of different plant species for improving soil quality for stormwater runoff reduction.

Previous studies demonstrated that applying organic amendments was successful in leading to effective vegetation establishment. The addition of organic matter-rich amendments into poor soils provided the necessary carbon (C) for vegetative growth. The next few paragraphs will provide more information about these applications. Composts can be classified based on the type of parent material, product maturity, amount of foreign matter in the product, particle size, organic matter content, concentrations of heavy metals, and others. Amending agricultural soils with compost has been shown to decrease bulk densities (Landschoot and McNitt 1994; Cogger 2005), increase in infiltration rates (Landschoot and McNitt, 1994; Aggelides and Londra 2000; Curtis et al. 2007), and increase water-holding capacity (Pandey 2005; Loper 2009; Weindorf et al. 2006). The use of composted material as a means of improved vegetation establishment has been reported in many studies (Glanville et al. 2004; Harrell and Miller 2004; Curtis and Claassen 2007; Mukhtar et al. 2008; Hansen et al. 2012). Compost has also been used in construction-related transportation projects in several states (USEPA, 2003). Current research at the University of Maryland (UMD) has seen similar advantages to the use of compost in both field and greenhouse observations. Compost has been shown to beneficially modify many soil properties, including increased porosity and decreased bulk density, which led to increases in soil stability, aggregation, and water-holding capacity (Khaleel et al. 1981; Mitchell 1997; Kirchoff et al. 2003).

Table 2-1 List of major studies on the evaluation of roadside soil quality restoration practices. Asterisk (*) indicates the studies led by the current research team.

No	Title	Reference	Main Goal
1*	Nutrient transport, shear strength and hydraulic characteristics of topsoils amended with mulch, compost and biosolids	Pamuru et al. (2024b)	Evaluate the effects of three different organic amendments (wood mulch, leaf compost, and biosolids) on nutrient release (runoff and leachate), shear and soil hydraulic properties for roadside soil applications.
2*	Using organic amendments in disturbed soil to enhance soil organic matter, nutrient content and turfgrass establishment	Morash et al. (2024)	Evaluate the effects of three organic amendments (wood mulch, leaf compost, and biosolids) on soil fertility and the establishment of vegetation in disturbed roadside soil.
3*	Understanding the Effects of Slope Ratio, Straw Mulching, and Compost Addition on Permanent Vegetation Establishment and Runoff Quality Control	Owen et al. (2020)	Identify critical elements involved in runoff generation and quality from (1) compost media application with straw mulch application, (2) increased ratio of compost: topsoil, and (3) variations in slope ratio from length to height
4*	Shear and Hydraulic Properties of Compost-Amended Topsoils for Use on Highway Slopes	Duzgun et al. (2021)	Examine the shear and hydraulic properties of two types of composts, biosolids and leaf compost, and their blends with a topsoil for their potential use on highway slopes
5*	Achieving Highway Volume and Pollutant Reduction Using Vegetated Compost Blankets: A Guide	Davis et al. (2023)	Assess the efficacy of using a vegetative compost blanket to improve the effectiveness of a vegetated filter strip through stormwater volume reduction and water quality improvement and to quantify the potential impact of compost leaching on receiving waters.
6*	Use of Compost for Permanent Vegetation Establishment and Erosion Control	Owen et al. (2019)	Evaluate the performance of select compost products in establishing permanent vegetation as part of construction site erosion prevention systems
7	Storm Water Infiltration and Pollinator Habitat Zones Along Highways	McLaughlin et al. (2020)	Assess tillage and adding amendments and planting different species for improving density and maintaining perviousness of subsoils during construction.
8	Investigation of Tillage and Soil Amendments to Increase Infiltration in Vegetated Stormwater Controls	Heitman and McLaughlin (2017)	Assess the impact of tillage, compost and combination of tillage and compost for improving infiltration
9	Reducing Stormwater Runoff Volumes with Biochar Addition to Highway Soils –	Imhoff et al. (2019)	Evaluate the impact of biochar on stormwater management
10	A Multi-Year Study of Tillage and Amendment Effects on Compacted Soils	Mohammadshirazi et al. (2017)	Evaluate the effects of tillage in compacted soils, with and without amendments, on soil density, infiltration rate, and vegetative growth
11	Changes in Soil Carbon Pools and Microbial Mass from Urban Land Development and Subsequent post-Development Soil Rehabilitation	Chen et al. (2013)	Evaluate the post-development soil rehabilitation on soil C pools and microbial biomass carbon

No	Title	Reference	Main Goal
12	Effect of Amendment Type and Incorporation Depth on Runoff from Compacted Sandy Soils	Bean and Dukes (2015)	Evaluate the hydrologic response of potential treatments for mitigating urban soil compaction
13	Remediation to Improve Infiltration into Compact Soils	Olson et al. (2013)	Investigate tilling and compost addition to improve infiltration rate
14	Soil Compaction and Growth of Woody Plants	Kozlowski (1999)	Impact of logging vehicle traffic on rural roadside vegetation establishment

Soil rehabilitation practices of organic matter incorporation can be used to enhance urban soil C reserves. In a field study in Tacoma, Washington, Brown et al. (2012) demonstrated the potential for C sequestration in urban soils via compost amendment and calculated that these amendments could result in 0.22 Mg C/ha carbon sequestration per year for the pervious land area of the city. Loper et al. (2010) reported that a single compost amendment tilled into the top 6 inches of surface soil increased soil organic matter compared to unamended control after one year in simulated new residential landscapes in Florida. The addition of organic soil amendments has been recommended for use in urban landscapes to improve disturbed, highly modified, or degraded soils (Cogger, 2005; Sæbø and Ferrini, 2006; Larney and Angers, 2012; Sloan et al., 2012).

While use of compost has shown promise for roadside vegetation improvement, its availability can be limited in certain parts of Minnesota. The quality of composts can be variable depending on the source material and processing procedure. On the other hand, commercially accessible proprietary amendments are available in many locations via local suppliers and possess consistent quality.

Proprietary amendments have demonstrated effectiveness in enhancing turfgrass establishment from seed or sod (Linde and Hepner, 2005). Certain soil amendments (e.g., synthetic slow-release fertilizer, natural-based fertilizer) have demonstrated the ability to hasten vegetation establishment in soils of varying quality in Rhode Island (Brown and Gorres, 2011). Watkins and Trappe (2017) tested a wide variety of proprietary amendments to improve vegetation establishment and recommended certain amendments to be used in such applications.

In Minnesota, all levels of government have shown concern over roadside maintenance due to both safety and aesthetic reasons, which led to the publication of “The Best Practices Handbook for Roadside Vegetation” by the Minnesota Local Road Research Board in 2000 (manual number 2000-19). Seven best practices were identified in the manual. An updated manual was published again in 2008, which incorporated additional best practices along with the originally proposed ones. Among these practices, integrated construction and maintenance practices are one of the most important (Johnson, 2008).

According to Johnson (2008), best management practices are (1) develop an integrated roadside vegetation management (IRVM) plan, (2) develop a public relations plan, (3) develop a mowing policy and improved procedures, (4) establish sustainable vegetation, (5) control noxious weeds and prevent the establishment of new invasives, (6) manage living snow fences, (7) use integrated construction and maintenance practices, (8) manage roadside vegetation for wildlife and vehicle safety.

Use of native plants is important. Native plants are usually more resistant to stresses and require less maintenance. According to Johnson (2008), there are three main reasons for preserving native plants: (1) environmental reasons as there is no substitute for original wild species and many native wildlife depends on native vegetation; (2) economic reasons, as native plants are more resistant to stresses and require less maintenance; (3) aesthetic reasons as native species provide seasonal color changes along roadsides. The following paragraphs describe some of the native plant species.

Big Bluestem *(Andropogon gerardii)* is a warm seasoned perennial branch grass, which grows about 4-8 ft long and is a very common plant in northern America. This grass is famous for its drought tolerant characteristic. In the late summer, the grass develops green foliage and purplish flowers.

Indian Grass *(Sorghastum nutans)* is a very attractive, warm season green grass with a golden sheen of flower at the top. The shoot of this grass plant grows about 3-7 ft, and they grow best in deep, well-drained soil. They are widely used for biomass production and erosion control.

Slender Wheatgrass *(Elymus trachycaulus)* is a native grass commonly used in western Canada and the US (Figure 2.1). They are widely used for soil salinity prevention and mine reclamation. It is a cool seasoned perennial plant and reaches a height of 20-40 in (Tilley et al., 2011). Seedlings are vigorous and provide good initial plant cover in seed mixtures. Figure 2.1 represents slender wheatgrass seed production in Idaho (Tilley et al., 2011).

Figure 2.1 Wheatgrass seed production in Idaho.

Kalm's Brome *(Bromus kalmii),* also known as Prairie Brome, is a winter-seasoned short-lived grass plant that grows about 2 ft tall. Prairie Brome is an attractive early flowering roadside vegetation. The grass flowers from July to mid-August and grows both in dry and moist lands.

Black-Eyed Susan *(Rudbeckia hirta)* is an annual to short-lived perennial wildflower with bright yellow flowers and dark centers. It is native to central and eastern USA. They usually occur atop 1-2 ft. stems and have oval shaped leaves. They are usually 12-39 inches in height and 12-18 inches in width.

Purple Prairie Clover (*Dalea purpurea*) is a widespread perennial flower that is native to North America. It is found in tallgrass, shortgrass, or mixed grass prairies. They can grow up to 8 to 35 inches tall with a woody stem. They have a cone-like flower head which gives them a distinct characteristic. It can be grown in a wide range of soil characteristics if the site is well drained. This flower is well known for attracting pollinators.

Canada Milk Vetch *(Astragalus canadensis)* is a perennial plant that is found throughout the USA and Canada. This plant is very adaptable and can grow in a variety of environments. They can grow to 18-42 inches tall. They are also known for attracting pollinators.

It can be concluded that sustainable and economic vegetation establishment is a complex process which demands participation from multiple stakeholders and depends on a variety of factors such as types of vegetation desired, soil condition, roadway traffic, roadway use (e.g., low volume vs high volume) and visibility, and roadway location. Since roadside vegetation establishment is directly related to sediment control, stormwater runoff, and soil erosion, the best management practices relating to these topics are also relevant. Some important best practices can also be found in "Erosion Control Handbook (number II)" by MnDOT and "The Erosion Control Handbook for Local Roads" published in 2003 by the Local Road Research Board (Johnson, 2008).

2.2 Site Conditions

Vegetation establishment relies heavily on local site conditions. Soil physical and chemical properties, plant characteristics, topography, and local climate conditions all fall under the broad term of site conditions. Appropriate site conditions need to be determined before implementing any vegetation establishment strategy. The following sections describe some important site conditions.

2.2.1 Soil

Selecting the right and most appropriate types of seeds and amendments and their application rates for vegetation establishment on roadsides after construction is significantly dependent on the soil types and texture. Not all types of soil are ideal for vegetation establishment. Ideal soils for healthy vegetation growth maintain a balance among mineral components (feldspar, mica, quartz), organic matter, air, and water. Organic matter provides nutrients, water is essential for plant growth (Rice, 2002). Road construction usually strips off the topsoil to reuse it for vegetation establishment.

Alterations to soil structures are detrimental to plant growth. Roadside compaction usually leads to such an alteration in the soil structure and fabric. For accurate assessment of these changes, measurements of soil bulk density are not adequate (Horn & Rostek, 2000). Soil strength, aeration, water, thermal, and structural characteristics are found to be the important properties that can be measured to understand soil behavior and its impact on vegetation establishment (Dexter, 1997; Horn & Rostek, 2000; Lipiec & Hatano, 2003; McQueen & Shepherd, 2002).

Soil grain size distribution, porosity, permeability, organic content, and water holding capacity are some of the other important factors that affect seed germination, seedling emergence, and optimal plant growth (Alam & Salahin, 2013).

2.2.2 Topography

Topography is one of the main factors that affect vegetation growth. While steeper slopes are more prone to soil erosion and runoff, flatter slopes retain more water and sediment. Relationships between topography and crop yield have been studied in the past. Topographic attributes from digital elevation models, such as slope, aspect, wetness index, flow direction, flow length, and flow accumulation, are important topographical and hydrological parameters that can affect plant growth (Bakhsh et al., 2000; Jenson & Domingue, 1988; Kravchenko & Bullock, 2002; Kravchenko & Bullock, 2000; Kumhálová et al., 2011).

Recently Owen et al., (2020) studied the effect of different slope angles (20H:1V, 6H:1V, 4H:1V, and 2H:1V) on vegetation establishment. They determined that steeper slopes resulted in larger nutrient and sediment mass export than shallower slopes. In general, flatter slopes are preferred for roadside vegetation establishment for easier mowing, spraying, and other maintenance activities (Johnson, 2008).

2.2.3 Vegetation

Roadside vegetation provides many benefits, such as preventing dust pollution on roads, providing micro habitats for some animals, adding aesthetics to the roadside users, and reducing runoff and erosion (Milton et al., 2015). Roadside vegetation must withstand multiple stresses like drought, cold, heat, disease, and exposure to deicing salts used during winter. Previous research has determined the cool season turf grass as a good candidate for high quality roadside vegetation capable of withstanding these stresses. Turfgrass mixtures that included high proportions of fine fescues, especially hard fescue and slender creeping red fescue have generally performed well (Friell et al., 2014; Kranz, 2021). Friell et al., (2014) studied the salt tolerance of different turfgrass species and summarized salt tolerance and roadside performance of turfgrass species based on existing literature (Table 2.2).

Table 2-2 Qualitative summary of salt tolerance and general roadside performance of turfgrass species, based on consensus of existing literature (Friell et al., 2014)

Species	Scientific Name	Salt Tolerance*	Roadside Performance*
Kentucky Bluegrass	*Poa pratensis*	-	-
Perennial Ryegrass	*Lolium penne*	0	--
Tall Fescue	*Festuca arundinacea*	+	+
Slender Creeping Red Fescue	*Festuca rubra ssp. litoralis*	++	++
Strong Creeping Red Fescue	*Festuca rubra ssp. rubra*	+	+
Hard Fescue	*Festuca trachyphyll*	0	++
Sheep Fescue	*Festuca ovina*	0	++
Chewings Fescue	*Festuca rubra ssp. fallax*	--	-
Creeping Bentgrass	*Agrostis stolonifera*	+	0
Colonial Bentgrass	*Agrostis tenuis*	0	+
Redtop Bentgrass	*Agrostis alba*	-	+
Alkaligrass	*Puccinellia spp.*	++	-
Prairie Junegrass	*Koeleria Macrantha*	-	--
Tufted Hairgrass	*Deschampsia cespitosa*	-	--

*(--) Very Poor, (-) Poor, (0) Moderate, (+) Good, (++) Very Good

Ratings are based on a qualitative overview of existing literature, as described in Friell et al., (2014)

2.3 Material Characterization

2.3.1 Plant Types

This MnDOT study decided to use a seed mix with blends of warm and cool season grasses and a few forbs rather than using non-native turf grass species. This mixture represents 75% of native plantings on the road right of way. Native plants may be preferred to since they are usually more resistant to stress and require less maintenance. Table 2.3 summarizes the plant types that will be present in the seed mixture. These plant types are described briefly in the introduction section.

Table 2-3 Plant types in the seed mixture and application rate

Common Name	Scientific Name	Percent of Mix (By Weight)
Big Bluestem	*Andropogon gerardii*	20
Indian Grass	*Sorghastrum nutans*	20
Slender Wheatgrass	*Elymus trachycaulus*	30
Kalm's Brome	*Bromus kalmia*	20
Black-Eyed Susan	*Rudbeckia hirta*	5
Purple Prairie Clover	*Dalea purpurea*	3
Canada Milk Vetch	*Astragalus canadensis*	2

2.3.2 Compost

According to the US Composting Council (USCC), "Compost is the product resulting from the controlled biological decomposition of organic material that has been sanitized through the generation of heat and stabilized to the point that it is beneficial to plant growth" (USEPA 2012).

The production of compost is basically a biological process in which organic materials are decomposed to humus-like substance by aerobic microorganisms. Microorganisms use organic materials as a food source and produce heat, carbon dioxide, water vapor and complex organic compounds. The resulting product is richer in nutrients and more stable than the original organic material. Moreover, compost improves soil physical and chemical properties when added to soil. However, compost properties vary significantly depending on the organic matter used and composting procedure that is followed. The composting process is usually affected by microorganisms, organic feedstock, and environmental factors (Annabi et al., 2007; Bastida et al., 2010; Cayuela et al., 2009; de Araújo et al., 2010; Duong, 2013; Epstein, 1997; Farrell & Jones, 2009; Wiley & Pearce, 1957).

Complete composting processes go through mesophilic, thermophilic, secondary mesophilic, and maturation phases. In the primary mesophilic phase, primary decomposers break down easy to digest compounds (e.g., sugars, proteins) and generate heat that kills most of the organisms. At the end of this phase, the dormant thermophilic bacteria become active and start the thermophilic phase. These bacteria continue generating heat which kills harmful pathogens, weeds, and insect larvae. At the end of this phase, heat reduces, and the secondary mesophilic phase begins. In this phase, bacteria, fungi, and actinomycetes breakdown hemicellulose, cellulose, and some lignin. Non-degradable compounds are formed in the maturation phase. The final compost material has a lower bulk density than its original form, and the original organic materials are no longer recognizable. The material has a dark crumbly appearance accompanied by an earthy odor (Diaz et al. 2007)

Though various organic materials can be used as a starting material, ultimately composting can be divided into two groups: biosolids and green waste. Biosolids-derived compost usually comes from wastewater treatment plants and are the product of composted and dewatered residual material mixed with a bulking agent. Green waste compost can be made from a variety of materials such as animal manure, food waste, crop residue, trees, shrubs, turfgrass, and wood byproducts (Owen et al., 2020). If the composting process is completed successfully then the resulting product is stable and odor free, but premature composting can result in odorous product and may have negative effects on soils and plants (Epstein, 1997).

The carbon/nitrogen (C/N) ratio of a well-composted material is in the range of 10 to 15 (USCC 2001). The pH of a mature compost is around 7 (neutral pH), but in general pH of composts changes as the organic matter decays in different stages and releases organic acids (Duong, 2013). Compost materials can be high in salt content. Electrical conductivity (EC) is a measure of soluble salt content. Compost with high salt content can be detrimental to plant growth; EC of mature compost should be within the range of 1 to 3 dsm^{-1} (Tognetti et al., 2007).

Composting can be beneficial to the environment in many ways. It replenishes soil organic matter and supplies plant nutrients (Sanchez-Monedero et al., 2004; Tejada et al., 2009). Soil organic content is important in improving physical, chemical, and biological properties that are needed for vegetation establishment. Soil structure is improved by binding between organic matter and clay particles via cation bridges and through stimulation of microbial activity, root development, and plant growth (Farrell & Jones, 2009; Gao et al., 2010). Healthy vegetation establishment requires nutrients in the soil, and organic matter is a significant reservoir of nutrients (Baldock, 2007). However, organic Nitrogen (N) and Phosphorous (P) in the compost must be mineralized before it can be taken up by plants. As a result, plant uptake of N and P from compost can be lower than from inorganic N and P fertilizers (Ebid et al., 2008; Odlare & Pell, 2009).

2.3.3 MnDOT Grade 1, 2, 3 compost

In Minnesota, Grade 1 and Grade 2 compost are mostly available. Grade 3 compost is a blend of these two composts (90% Grade 2 compost and 10% Grade 1 compost). The following sections provide a brief description and material properties of these composts.

According to the Minnesota Department of Transportation (MnDOT) specifications, composts cannot contain chemical contaminants, including pesticides, that would have toxic effects on soil organisms, plants, or animals. Grade 1 compost is derived from the decomposition of animal material and animal byproducts. It has a texture like organic soil. Grade 1 compost should possess other properties listed in Table 2.4.

Grade 2 compost is produced from yard waste, leaves, or blends. The texture of this compost should be like a shredded peat and humous rich. Table 2.5 summarizes the grade 2 compost requirements according to MnDOT specifications.

Table 2-4. Grade 1 compost requirement according to MnDOT specification 3890 (MnDOT, 2018)

Grade 1 Compost Requirements	
Organic matter content (dry weight)	≥ 30%
C/N ratio	6:1 – 20:1
N:P:K ratio* (% dry weight)	2:2:1 – 4:4:2
pH	5.5 – 8.0
Moisture content	35% – 55%
Bulk density	700 lb per cu. yd – 1,600 lb per cu. yd
Inert material	≤ 3% at 0.15 in
Soluble salts	≤ 10 mmho per cm
Germination test	80% – 100%
Screened particle size	≤ ¾ in

Table 2-5. Grade 2 compost requirement according to MnDOT specification 3890 (MnDOT, 2018)

Grade 2 Compost Requirements	
Organic matter content (dry weight)	≥ 30%
C/N ratio	6:1 – 20:1
N:P:K ratio* (% dry weight)	1:1:1
pH	5.5 – 8.0
Moisture content	35% – 55%
Bulk density	700 lb per cu. yd – 1,600 lb per cu. yd
Inert material	≤ 3% at 0.15 in
Soluble salts	≤ 10 mmho per cm
Germination test	80% – 100%
Screened particle size	≤ ¾ in

2.3.4 Biochar

Biochar is a substance which looks like charcoal and is produced from high temperature processing of biomass in a controlled process called pyrolysis. Black Carbon (BC) is the main component of biochar, and it is produced by incomplete combustion of organic materials (Goldberg, 1985; Schmidt et al., 1999). BC is resistant to degradation and decomposition because of its condensed structure (Glaser et al., 1998; Kuzyakov et al., 2009).

Schulz and Glaser (2012) studied the effect of biochar mixed with organic and inorganic amendments on oat production in greenhouse experiments. They determined that biochar and compost addition to poor soils yielded the highest plant growth in a two-growth period, second only to compost addition, compared to mineral fertilizers alone (Figure 2.2). Biochar and compost addition increased organic carbon content, but its impact on cation-exchange capacity (CEC) was negligible. However, other studies have observed that biochar effectively increases cation-exchange capacities of soils. A study by Laird et al. (2010) on Mesic types of soil from Boone County, 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).

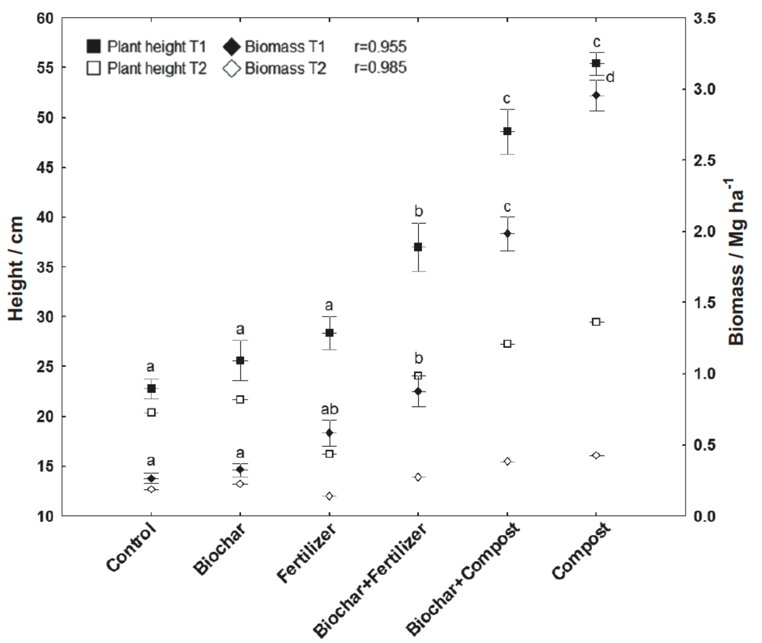


Figure 2.2. Plant height and plant biomass after first (T1) and after the second harvest (T2). Whiskers represent ± standard error of the mean (n=5). (Schulz and Glaser, 2012)

2.3.5 Source Separated Organic Materials (SSOM)

Source Separated Organic Materials (SSOM) (e.g., food waste, compostable items, and yard waste) refers to recyclable materials that are collected for use, reuse, reclamation, or recycling, and, in Minnesota, are managed by professional composters according to the Minnesota Pollution Agency. A SSOM permit is required for these facilities to operate, and the local waste chain runs the programs. SSOM can be a viable option to be used as an organic amendment to soil. If used properly, it can increase the soil physical and chemical properties that are necessary for vegetation growth.

2.3.6 Proprietary Soil Amendments

Proprietary soil amendments are fertilizer-type products that are mixed with topsoil to improve its crop growing capacity. Different types of proprietary soil amendments have different functions in soil. They have the quality to improve specific properties of problematic soils. They are generally applied in a small amount on the topsoil which results in better root growth and ultimately strong vegetation establishment. Numerous types of organic and inorganic soil amendments are available to modify soil, and their effectiveness depends on soil properties, compositions, and amount needed (Turgeon, 1991).

2.3.7 Biotic Soil Media (BSM)

Biotic soil media is an engineered soil that contains recycled, biodegradable fibers, bio-stimulants, biological inoculants, mycorrhizae, biochar, and other nutritive additives. Multiple companies produce BSM materials, and it has been proven to be effective in increasing soil chemical and physical properties that are crucial for vegetation growth.

Verdyol Biotic Earth Black is a BSM which is an extremely active hydraulically applied mulch and growth medium that includes a high concentration of soil nutrients. This product is designed as an alternative to topsoil or compost. It is usually applied hydraulically at a rate of 3,500 lbs/acre, and it is claimed that the application rate of this product does not change significantly with the slope or organic content of the existing soil (Premier Pacific Seeds, 2021). It is made with products (e.g., natural fibers, mycorrhizal fungi, bacteria, and natural growth stimulants). Material composition of this product by volume is summarized in Table 2.6. Laboratory analysis of this product showed that the total organic content of this material was over 95%, the C/N ratio was 31/1, and moisture content and pH are around 31%, and 5.5, respectively.

Table 2-6. Material composition of Verdyol Biotic Earth Black (Biotic, 2021)

Material Composition	Volume (%)
Thermally and mechanically processed straw and flexible flax fibers (FFF)	40
Sphagnum Peat Moss	57
Trace minerals, sugars, starches, proteins, fiber and 16 amino acids	1.26
Mycorrhizae	<1

2.4 Laboratory Testing of Soil and Compost

Physical and chemical properties of soil, compost, and proprietary soil amendments influence vegetation establishment. Some important physical parameters of soil include saturated hydraulic conductivity, soil bulk density, and moisture content. Chemical properties of soil and compost include micro/macro nutrients (nitrogen, phosphorous, and potassium), pH, electrical conductivity (EC), cation exchange capacity (CEC), and soluble salt contents. Landschoot (1996) provided a guideline for choosing a compost (Table 2.7); however not all compost can fall into this category. It is important to know the exact properties of a compost before using it for a particular application.

Table 2-7 Acceptable chemical properties of compost (Landschoot, 1996)

Chemical Properties	Acceptable Values
Carbon : Nitrogen (C/N) Ratio	Below or equal to 30/1
Nitrogen	30-40%
Phosphorus	15-20%
Potassium	15-40%
pH	6.0 – 8.0

C/N ratio in composts is an important parameter. If this ratio is above 30/1, soil microorganisms can inhibit nitrogen mobilization and make it unavailable for vegetation growth. According to Landschoot (1996), C/N ratios of the majority of the commercial composts are below 30/1. Table 2.8 provides a summary of methods and/or specifications that can be used in determining soil chemical properties.

Table 2-8. Summary of soil chemical tests from literature

Chemical Property	Standard/Method	Device	Source
pH	ASTM D4972-01	Oakton PC 2700 Meter	(Yang et al., 2020)
	1:1 soil: distilled water	Glass Electrode	(Koide et al.,2018)
	1:2.5 water or KCl to soil extracts	Electrode	(Rodríguez-Vila et al., 2016)
	Method 9045D, USEPA 2004		(Evanylo et al., 2016)
Electrical Conductivity (EC)	C1A/3, 2013	Oakton PC 2700 Meter	(Yang et al., 2020)
Soil Alkalinity	Titration Method	HACH alkalinity kit	(Yang et al., 2020)
Cation Exchange Capacity (CEC)	Water Leach Test (ASTM D3987-04)	-	(Ceylan et al., 2019)
Total C and Total N	Dry combustion	VarioMax CNS analyzer	(Evanylo et al., 2016; Koide et al.,2018)
	Dry Combustion	Leco CN-200 analyzer	(Rodríguez-Vila et al., 2016)

2.5 Greenhouse Experiments

Greenhouse experiments provide an opportunity to study plant and vegetation growth under regulated climatic conditions. They have been widely used in crop and soil science, food production, and in plant science related research. Researchers have conducted greenhouse experiments to study the effects of organic and inorganic amendments, biochar on roadside plant growth, soil nutrients, and stormwater runoff (Duong, 2013; Kranz, 2021; Liu et al., 2019; Owen et al., 2020; Schulz & Glaser, 2012). Greenhouse experiments can also effectively be used to quantify soil erosion (Owen et al., 2020).

Pot and mesocosm studies are two types of greenhouse experiments that were conducted in this research. Mesocosm studies help to understand biological and ecological complexities and bridge the gap between laboratory scale experiments and actual habitat studies (Sharma et al., 2021). Mesocosms can be defined as experimental enclosures from one to several thousands of liters that are used to replicate biological complexities at larger scales (Stewart et al., 2013). Effects of climate and organic-inorganic amendments to roadside vegetation establishment and erosion control can be experimentally evaluated in a mesocosm study. The following sections briefly describe findings from different studies on greenhouse experiments using compost.

2.5.1 Effects of Compost on Soil Properties in Greenhouse Experiments

Rodríguez-Vila et al. (2016) conducted a greenhouse pot study to assess the effects of compost and biochar amendments on mine soils in Spain. They carried out greenhouse experiments with 20%, 40%, 80% and 100% of compost and biochar mixture and *Brassica juncea* plants to reduce the copper contamination. The amendment was a mixture of 95% compost and 5% biochar. The mine soil was acidic (pH= 2.7), and concentrated with heavy metals (e.g., Cu, Al, Co, Fe and Ni). It was speculated that the application of compost and biochar along with *Brassica juncea* plants would be able to reduce the infertility of the mine soil caused by the heavy metal contamination.

After three months, a significant improvement was observed in pH (2.7 to 8.7), total nitrogen (TN), potassium (K), phosphorus (P), magnesium (Mg), and sodium (Na) content of the mine soil. Higher proportion of compost and biochar mixture samples (e.g., BC80 and BC100 in Figure 2.3a) resulted in increased TN, Mg, and K as compared to the control samples (e.g., A0, A0P in Figure 2.3a). The presence of zinc (Zn) was determined to be present at negligible levels when higher proportions of compost were used (e.g., BC80 and BC100 in Figure 2.3d). As stated by Al Chami et al. (2013), excess amount of compost may reduce Zn concentration in soil and the most probable reason behind this phenomenon is the molecular replacement of Zn by the organic content present in composts.

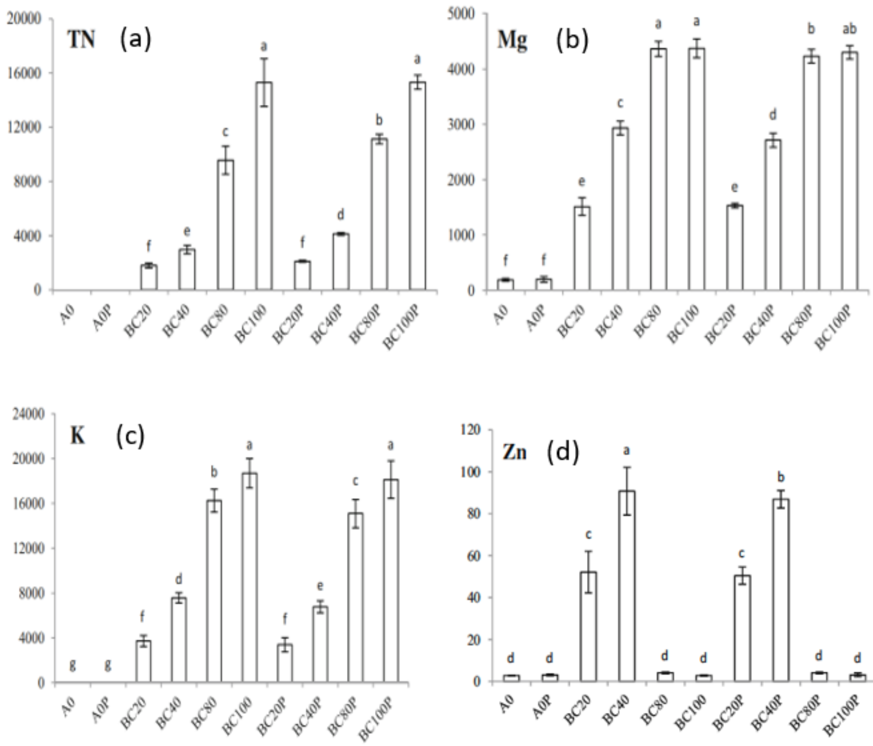


Figure 2.3. Improvement in a mine Soil reclaimed with compost and biochar. (a) Total Nitrogen (TN) content, (b) Magnesium (Mg) Content, (c) Potassium (K) content, and (d) Zinc (Zn) content. (Rodríguez-Vila et al., 2016)

A0 = 0% Amendment, BC20 = 20% amendment, BC40 = 40% amendment, BC80 = 80% Amendment, BC100 = 100% Amendment. P denotes soil samples with plants.

2.5.2 Compost Rate for Vegetation Growth

Compost increases soil organic matter and plant nutrients. As a result, it improves vegetation growth. The benefits of these improvements depend on compost properties and compost application rates.

Kranz (2021) studied the effects of compost rates on turfgrass establishment on disturbed urban soils. A set of greenhouse experiments were performed with various percentages (0%, 10%, 30%, 50% and 100% by volume) of two different types of composts to evaluate turfgrass establishment, quantity, and quality. The soil used for this study was a sandy loam (73% sand, 16% silt, 11% clay) and it was blended with McGill Sports Turf compost (New Hill, NC) or North Carolina State University campus compost. The McGill compost was a blend of green waste, food waste, biosolids, and woody materials, whereas the campus compost was a mixture of woody materials, yard waste, and food waste.

Visual assessment of turf quality was made using a scale of 1 to 9 (1=worst, 9=best) according to the National Turfgrass Evaluation Program (Morris & Shearman, 1998). The compost source or rate did not appear to interfere with seed germination. There was only a minor difference between the colors of turf grass with all rates of compost. The turfgrass cover ratings increased with time. The average height of the turfgrass increased with time.

From the observation of the growth of biomass in Figure 2.4, it was determined that the 100% compost rate produced a greater amount of biomass than the other rates. Other researchers also had similar results (Schulz & Glaser, 2012). All other compost rates produced the same amount of biomass. The greater biomass produced from 100% compost rate is probably due to the greater plant uptake of readily available N.

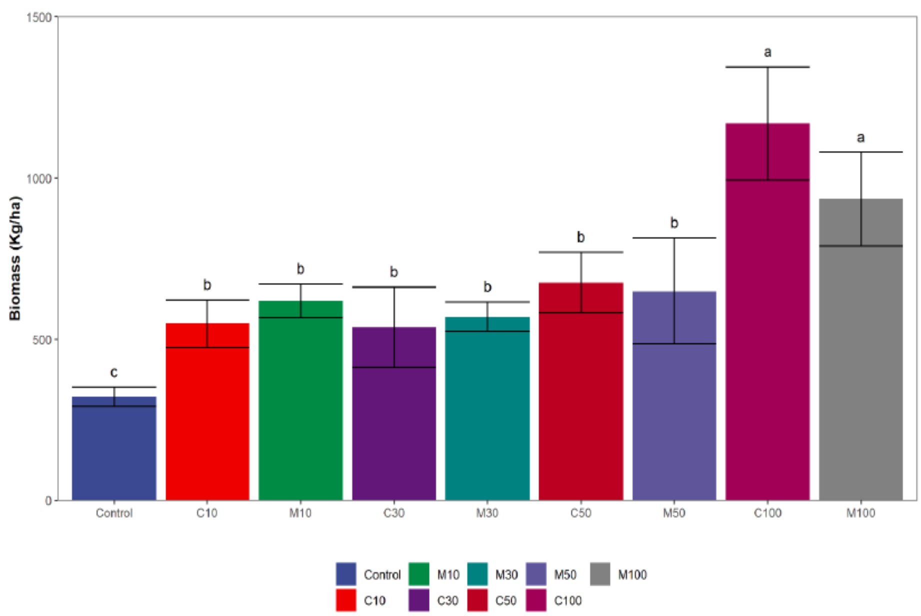


Figure 2.4. Turfgrass biomass production after 5-weeks. Comparative performance of different application rates of compost. (Kranz, 2021)

M10=10% compost, M30=30% compost, M50= 50% compost, M100= 100% compost, C10= 10% compost, C30= 30% compost, C50= 50% compost, C100= 100% compost (M= McGill Compost, C=Campus Compost)

Kranz (2021) concluded that compost application rate does not affect seed germination or quality of turf establishment. However, higher rates of compost were determined to have more vegetative cover and produced more biomass. This study also observed that increasing the compost rate clearly resulted in better turf grass quality, color, height, and cover compared to those with no compost. Figure 2.5 shows grass coverage with an increase in compost rates. 100% compost has the broadest grass coverage compared to the other percentages of compost.

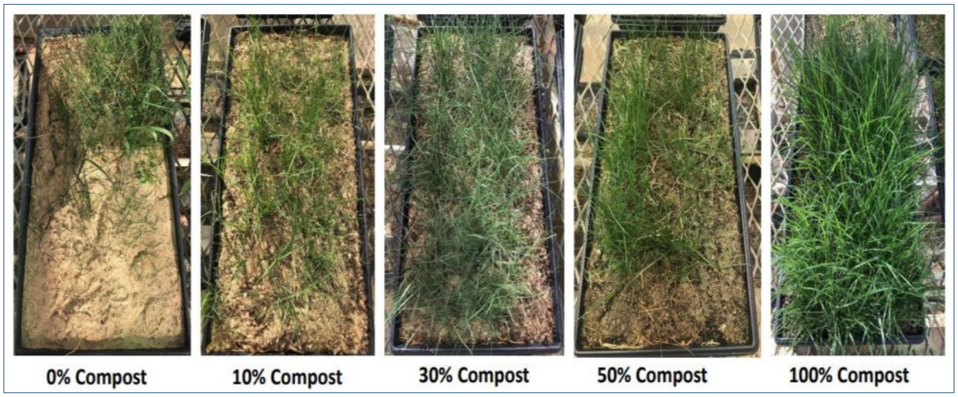


Figure 2.5.Effect of varying compost levels (0%, 10%, 30%, 50%, and 100%) on turfgrass growth prior to harvesting. (Kranz, 2021)

2.5.3 Effects of Compost Amendments on Plant Growth in Greenhouse Experiments

Duong (2013) conducted greenhouse experiments to evaluate the quality of biomass produced from vegetation growth in four different types of composts, specifically: Compost 1 (obtained from municipal solid waste), Compost 2 (same as Compost 1 but with coarser texture), Compost 3 (from kitchen waste and manure), and Compost 4 (from straw and chicken manure). Compost 1 was fine textured and had the highest concentration of total Nitrogen (N) and dissolved organic Carbon (C). Compost 2 was coarse textured and had the highest total organic C and moisture content. The electrical conductivity (EC) value was the highest in Compost 3. Compost 4 was medium textured and had the highest pH.

The results of this study showed that the compost type and its application time (e.g., spring or summer) affected the biomass growth and nutrient concentrations. Figure 2.6 shows that the highest biomass (shoot dry matter in this case) is obtained after 4 months during the springtime. Biomass production decreased during summer, then again it increased after 12 months. These results indicated that timing and season (temperature and daylight) had a great impact on the efficiency of composts on plant growth.

The results of the study also showed increased nutrient content (e.g., N and P) in the plant shoot due to compost amendment (Figure 2.7). The P content in the plant shoot increased over time. The high shoot P concentration is related to the available P in the soil. Compost 3 and 4 (C3 and C4) resulted in the highest P concentration at the end of the experiment (Figure 2.7a). The coarse-textured Compost 2 had the least effect on nutrient availability and plant growth due to low nutrient mobilization rate.

The shoot N concertation was high after 6 months (Figure 2.7b); however, shoot growth was the highest after 4 months (Figure 2.6). Higher shoot growth usually utilizes more N and resulted in lower N concentration after 4 months.

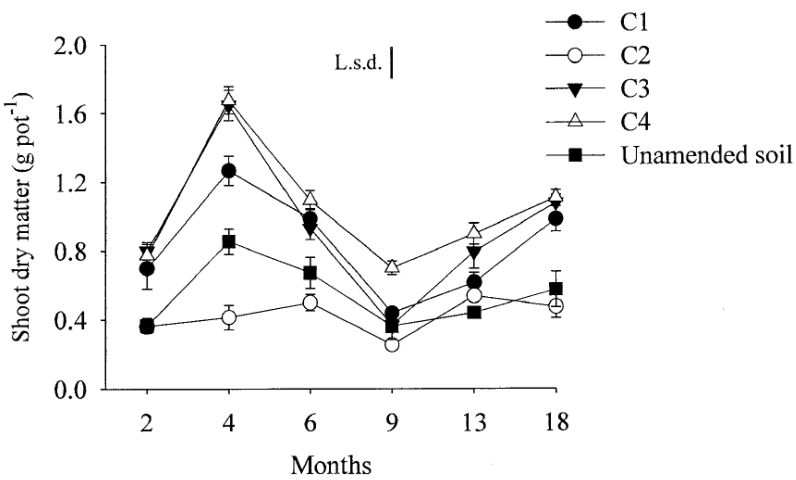


Figure 2.6. Plant shoot growth due to various compost addition. (Duong, 2013)

C1= Compost 1 C2= Compost 2 C3= Compost 3, C4= Compost 4, L.s.d=Least significant difference

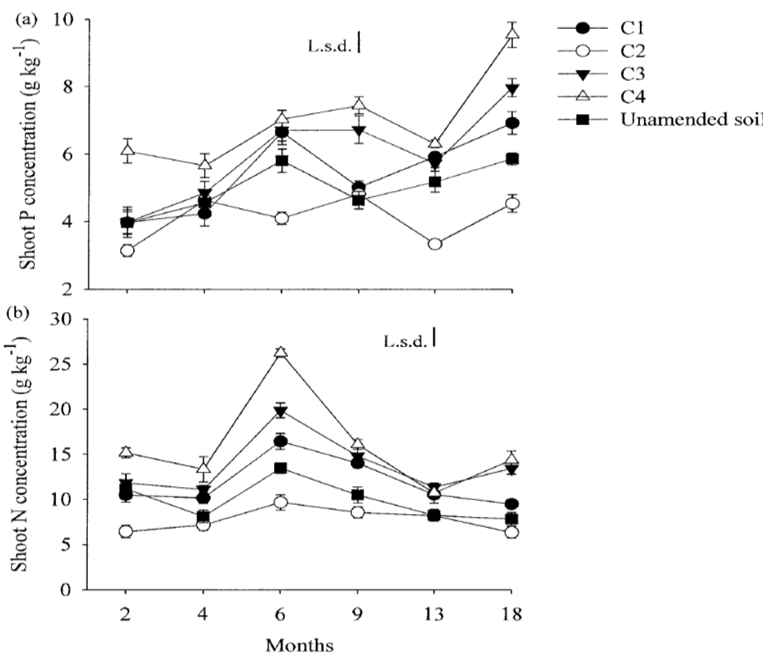


Figure 2.7. Plant shoot nutrients concentration due to various compost addition. (a) Phosphorus (P) concentration in plant shoot, and (b) Nitrogen (N) concentration in plant shoot. (Duong, 2013)

C1= Compost 1 C2= Compost 2, C3= Compost 3, C4= Compost 4, L.s.d=Least significant difference

2.5.4 Effects of Mixed Soil Amendments on Plant Growth in Greenhouse Experiments

Researchers have also used blends of organic and inorganic soil amendments to improve plant growth and the nutrient capacity of poor soils. Kargosha (2018) conducted a greenhouse pot study to understand the effects of potassium humate (K-humate) blended phosphate (P) amendment on annual Ryegrass (*Lolium multiflorum Lam.*). K-humate is manufactured from the alkaline extraction of brown coal (lignite). The inorganic fertilizer used was triple superphosphate (TSP) which contains 46% soluble P.

Four blends of triple superphosphate (TSP), and K-humate were used. Plastic pots were filled with 2.2 lb. (1 kg) of soil. Each amendment was applied at 0.4-inch (1-cm) depth of soil in the pot. Four replicates were conducted for each treatment. Figure 2.8 shows pictures of the set of pots tested during the greenhouse experiments.

After 12 weeks of seeding (Figure 2.9), the plants were removed from the soil and plants, shoots, and roots were oven dried to determine dried biomass weight. ANOVA analysis showed that the fertilizers had no significant effect ($p < 0.05$) on ryegrass shoot dry weight (SDW) and root dry weight (RDW) in Podosol. While root biomass varied between TSP and HBP (humate blended phosphate) fertilizers, these differences were not statistically significant ($p < 0.05$). The highest root biomass was recorded for HBP2 (0.61 g/pot), followed by HBP3-higher humate content (0.51 g/pot), while TSP had the lowest (0.42 g/pot).

Figure 2.8. Greenhouse pot study to understand the effects of humate blended fertilizer. (Kargosha, 2018)

Figure 2.9. Twelve weeks old Ryegrass (Lolium multiflorum Lam.) plants on Podosol soil. (Kargosha, 2018)

2.6 Field Experiments and Vegetation Growth Quantification

Although laboratory and/or greenhouse experiments provide fast information about plant growth in soils due to controlled environment capacities during testing, results obtained from greenhouse and field experiments may not simulate the field conditions in all cases (Forero et al., 2019). Even though long-term field observations are constrained by budget and time required for data collection, results collected from long-term field testing programs are quite reliable under any random atmospheric conditions (Körschens, 2006). Variations of biotic and abiotic conditions of soils, absence of various microorganisms, limited response of soils to environmental changes, and optimum values of N and C (most important elements of soil) are the most common limitations of greenhouse experiments (Casper et al., 2008; Körschens, 2006; Kuťáková et al., 2018; Wardle et al., 2004). The following sections briefly describe literature related to vegetation establishment in field experiments.

2.6.1 Site Preparation for Field Tests

Proper site construction is very important to ensure a stable platform for analyzing vegetation establishment. Field site preparations from some relevant studies are summarized below.

As stated by Kranz (2021), for preparing the site for compost and other amendments application, the topsoil and vegetation cover should be removed to expose the subsoil. Then, the subsoil should be tilled up to 6 inches and a 5% slope should be achieved to provide adequate drainage. Kranz (2021) constructed individual plots from wooden boards (10 ft length x 5ft width) with an isosceles triangle on the sloping end to channel water to collect runoff for chemical and sediment analyses (Figure 2.10).

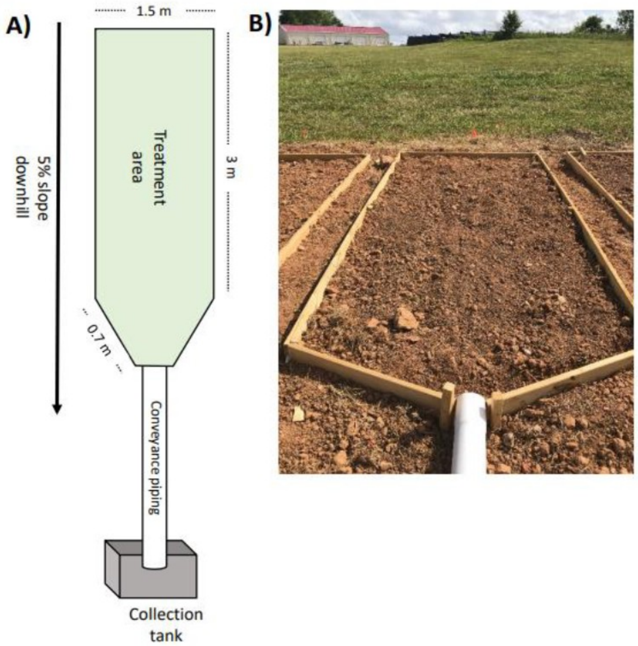


Figure 2.10. (a) Plan view of site configuration showing connection between plot areas and collection tanks, and (b) photo of the site configuration before treatment application (Kranz 2021).

Owen et al. (2020) conducted a field experiment on two sites (Hanover, MD and Upper Marlboro, MD). 15 plots were setup using 6 in. plywood dividers. Soil was excavated to 4 inches below the original topsoil in slopes ranging from 1:1 to 2:1. Vegetation growth and change in soil properties were

monitored for five different compost-soil media mixtures. Each plot was either 6 ft wide x 19 ft long (Hanover, MD) or 8 ft wide x 40 ft long (Upper Marlboro, MD). Figure 2.11 shows photos of these plots at both locations.

Figure 2.11. (a) Plots built at the Hanover, MD site after initial construction, (b) Upper Marlboro, MD site photo taken 87 days after slope establishment. (Owen et al. 2020).

2.6.2 Vegetation Establishment Measurement with Image Analysis

As mentioned before, many research studies have suggested compost as a beneficial element for vegetation establishment along roadside slopes. To quantify vegetation establishment researchers have used different techniques including image analysis and biomass measurements.

Owen et al. (2020) used an image-based approach to quantify vegetation growth. Image analysis was used to determine greenness of the grass coverage that correlated to vegetation growth. Photographs were taken every 14 days except for the winter months when plant growth was dormant. Captured images were cropped and color corrected to account for the different lighting conditions. The median greenness value was used as the thresholding limit for all images. Image analysis confirmed that with straw mulching, all compost-amended slopes achieved over 95% green vegetation cover within 60 days, whereas without mulching, the maximum green vegetation cover was only 31% after the same period. The benefits of straw mulch in keeping the soil moisture and other nutrients consistent within the treated soil medium were shown in earlier work (Edwards et al., 2000).

The study by Owen et al. (2020) showed that the biosolids compost was more effective than the green waste compost in establishing green coverage on both sites. While the green waste compost was slower to reach the peak greenness, it provided maximum coverage over time. Figure 2.12 demonstrates the proportion of green coverage of five media over the duration of three growth periods for Hanover site. It is seen that green coverage after the second growth period becomes statistically similar for both biosolids media types and topsoil/green waste mixtures.

The same study also found a negative trend in green cover with distance from the base of the slope (Figure 2.13). Green cover decreased with increased distance from bottom of the slope. This negative trend is attributed to the migration of both moisture and nutrients through the soil media, leading to a nutrient rich environment near the slope base.

Figure 2.14 shows the vegetation establishment rate as a function of percent compost for both biosolids and green waste composts. Owen et al. (2020) observed that vegetation growth rate decreased slightly with an increase in compost content after certain amount (approximately 30-35%), even though the decrease was statistically insignificant. As compost content increases, porosity increases, which can lead to faster evaporation, which is probably responsible for this decrease in vegetation growth (Owen et al., 2020).

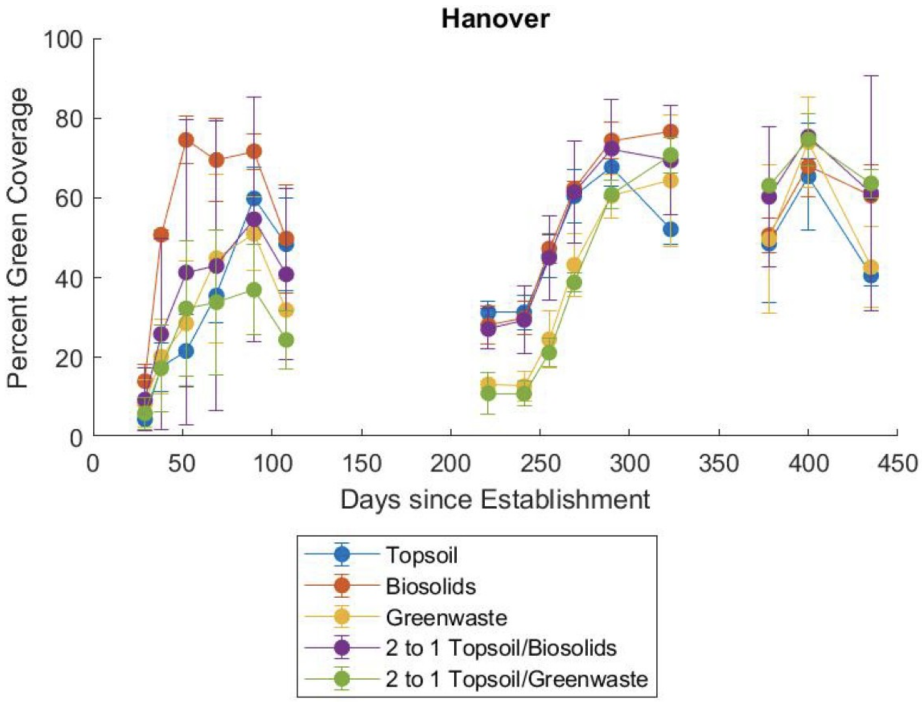


Figure 2.12. Greenness period of Hanover, MD site over three distinct growth period. (Owen et al. 2020)

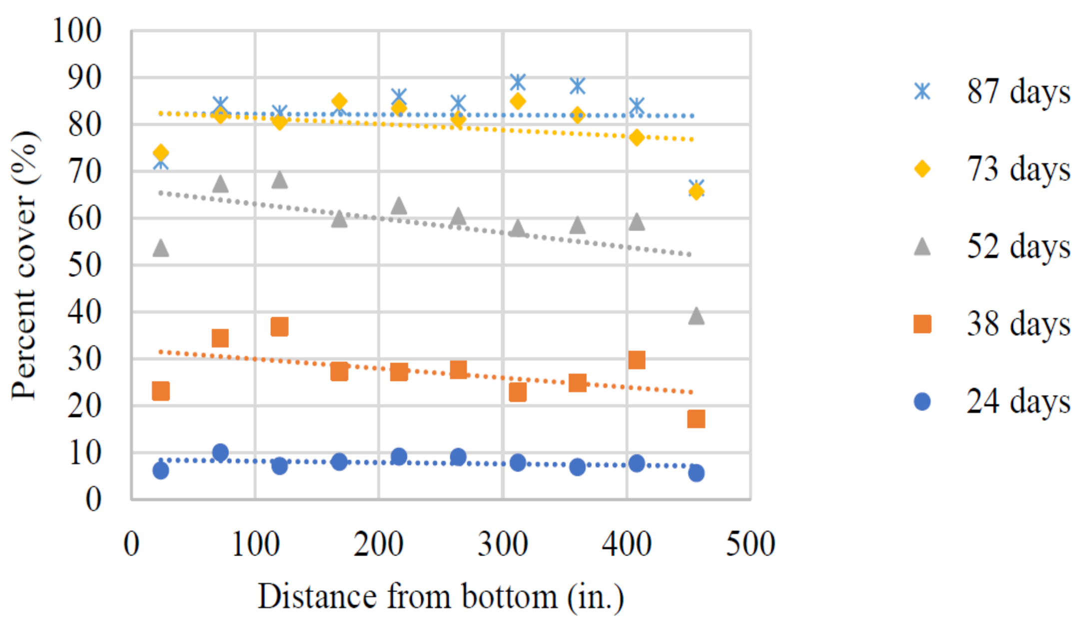


Figure 2.13. Growth with respect to distance from the bottom of the slope for Upper Marlboro site. 5 days of green coverage for a single topsoil was used to create this plot. (Owen et al. 2020)

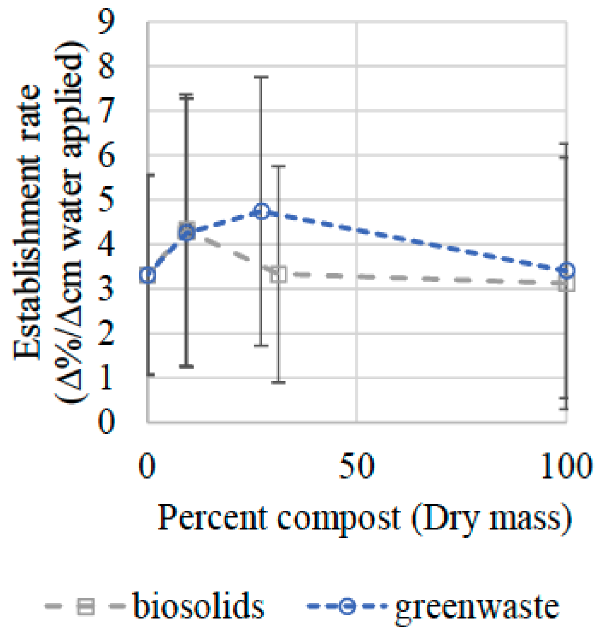


Figure 2.14. Average vegetation establishment rate for various percentages of compost mixture for green waste and biosolids. (Owen et al. 2020)

2.6.3 Vegetation Establishment Measurement Based on Biomass Growth

Vegetation cover can be measured in terms of biomass produced from the plants. A study conducted by Liu et al. (2019) quantified plant growth in terms of shoot and root biomass. Three different municipal composts were used in heavy metal contaminated soil. The composts were designated as compost 1: primary compost (MSW-C), compost 2: secondary compost (MSW-SC), and compost 3: aging compost (MSW-AC). MSW-C was obtained from sanitary waste composting site. MSW-SC used the same raw material as MSW-C but used a strip type composting method. MSW-SC compost samples were aged for 1 year after composting for 45 days and then used as raw material for the aging compost.

Sedum aizoon was the plant species used in this study. Plant biomass growth rates were determined by measuring the heights weekly. Final biomass was quantified after 3 months' growth. The plants were washed with distilled water after the harvest, and the fresh weights of the plant tissues were measured.

Eight different growing media were used in this study (explained in Figure 2.15). Figure 2.15 shows the above and underground biomass mass measured for different treatments. 25% compost application rate was found to be the optimum mixture, and 50% compost had lower average change in dry mass compared to that of no compost-remediated soil. The different maturity compost had significant effect on plant biomass growth, and the application of the aging compost demonstrated the most influence on plant biomass.

This study also found that greater plant height was associated with high compost application rate. The highest plant height was obtained for 50% treatment of MSW-AC. In addition to that, the roots lengths of plants in MSW-AC treatments were significantly longer than any other treatments.

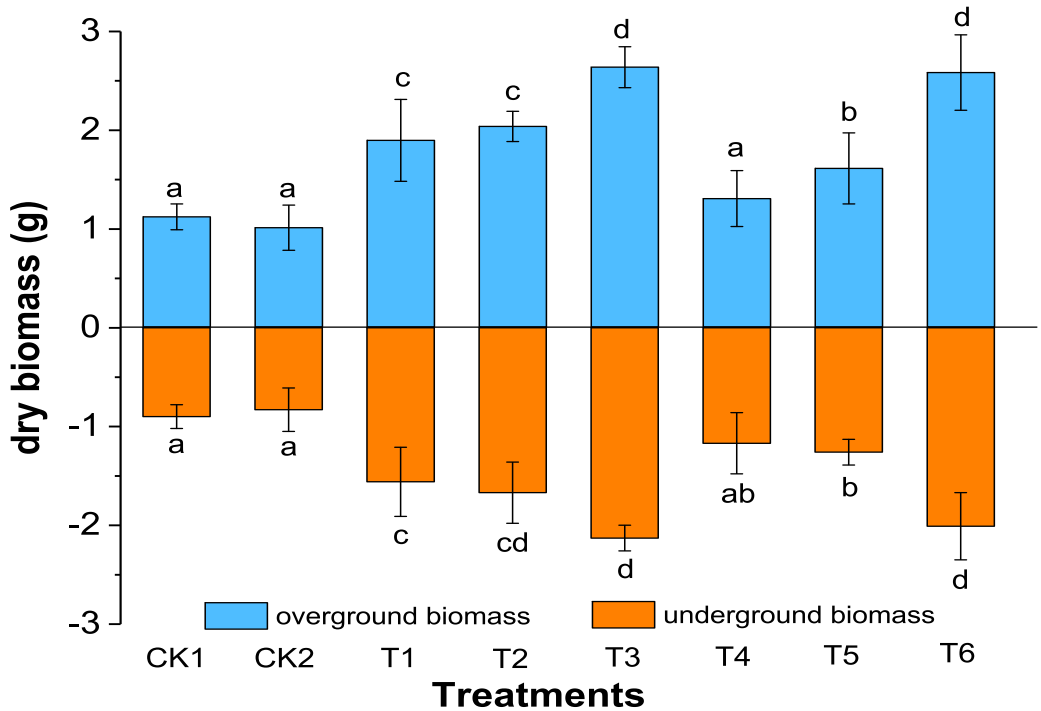


Figure 2.15. The aboveground and underground biomass in different substrates. (Liu et al., 2019)

CK1: original soil, CK2: heavy metal contaminated soil, T1: 25% compost 1 + 75% contaminated soil T2: 25% Compost 2+ 75% contaminated soil, T3: 25% Compost 3 + 75% contaminated soil, T4: 50% compost 1 + 50% contaminated soil, T5: 50% compost 2+ 50% contaminated soil, T6: 50% compost 3 + 50% contaminated soil. The data are presented as Mean ± SD with n = 3. Letters (a, b, and c) represent multiple comparisons at $p < 0.05$ for each level. Identical letters indicate no significant difference, while different letters denote significant differences between compost types, as determined by ANOVA.

2.6.4 Vegetation Establishment Measurement Based on Shoot and Root Dimensions

Large root volume indicates sufficient nutrients absorbed and reserved by the root. Some research showed that plant shoot and root volume can be used to quantify vegetation growth (Liu et al. 2019; McGrath & Henry 2016). The effects of composts on vegetation growth and root characteristics in a contaminated soil are summarized in Table 2.9.

Table 2.9 shows that plant height is significantly higher for all media treated with composts. In addition, root surface area for 50% compost remediated soil is less than that of 25% compost added soil. The maximum root volume (0.106 ± 0.004 inch^3) was observed for the T3 treatment which was the 25% compost-amended plant root. Both root surface area and length were higher for control groups. Liu et al. (2019) claimed that increase of root volume with addition of compost was a good indicator of absorption of nutrients and moisture by plants.

McGrath & Henry (2016) incorporated 5%, 10%, 25% and 50% compost by volume into a poor soil. Root extension and chlorophyll content were measured to monitor the plant growth. Trunk cross sectional area (TCSA), plant height, and shoot lengths were measured as an indication of plant growth. Figure 2.16a shows that shoot length was the highest for 25% organic amendment soil. Similarly, TCSA also increased with higher proportions of organic compost mixtures (Figure 2.16b). However, adding 50% of compost by volume reduced this parameter.

Table 2-9. The effects of composts on root development in contaminated soil (Liu et al., 2019)

Treatments	Height (in)	Root Length (in)	Root Surface Area (in^2)	Root Volume (in^3)
CK1	2.33±0.25	62.59±5.81	6.79±0.44	0.037±0.001
CK2	2.28±0.49	57.44±1.55	5.84±0.15	0.036±0.003
T1	2.72±0.46	18.27±2.81	2.71±0.15	0.038±0.003
T2	2.87±0.33	19.19±3.22	3.19±0.33	0.046±0.007
T3	3.15±0.34	31.87±0.92	5.14±0.38	0.106±0.004
T4	2.44±0.67	16.20±2.45	2.65±0.26	0.04±0.006
T5	2.52±0.15	16.50±3.15	2.69±0.64	0.043±0.002
T6	3.35±0.51	51.04±3.41	5.62±0.46	0.095±0.007

CK1: original soil, CK2: heavy metal contaminated soil, T1: 25% compost 1 + 75% contaminated soil T2: 25% Compost 2+ 75% contaminated soil, T3: 25% Compost 3 + 75% contaminated soil, T4: 50% compost 1 + 50% contaminated soil, T5: 50% compost 2+ 50% contaminated soil, T6: 50% compost 3 + 50% contaminated soil

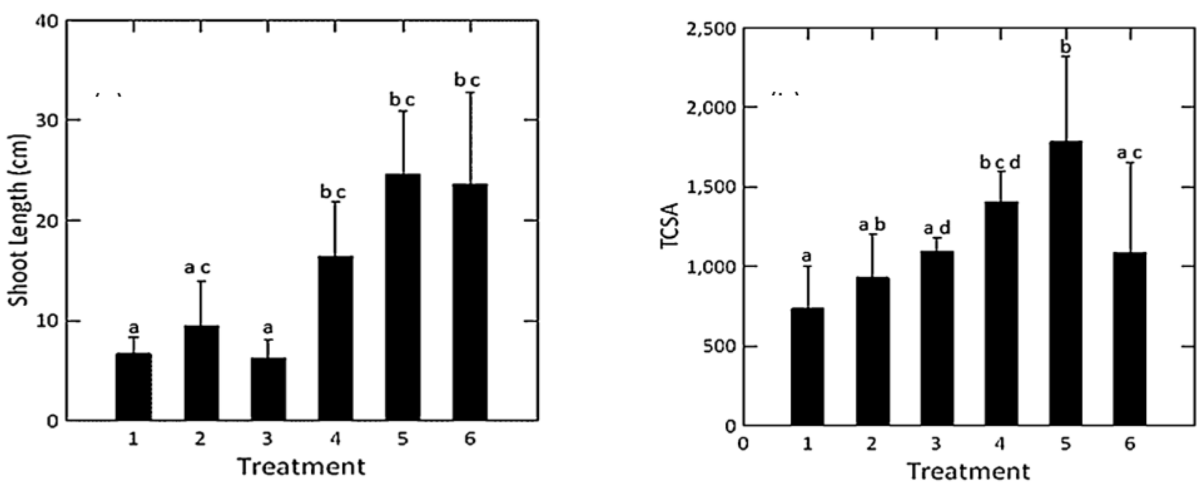


Figure 2.16 Effect of compost and organic amendments on (a) shoot length' and (b) trunk cross sectional area. (McGrath and Henry 2016)

Treatment 1: Control, Treatment 2: 50% compost backfilled in tree pit, Treatment 3: Subsoil + Till, Treatment 4: 10% Organic Amendment, Treatment 5: 25% Organic Amendment, Treatment 6: 50% Organic Amendment

Moreover, McGrath & Henry (2016) observed a significant increase in plant heights and chlorophyll contents due to addition of compost and organic amendments. Plant height was the highest for treatments with 10%, 25%, and 50% organic amendments (Figure 2.17a). Treatment 2 resulted in the lowest plant growth. Significant differences were observed in chlorophyll contents between organic-amended remediated treatment soils and the control (untreated) soils (Figure 2.17b). Chlorophyll content decreased at a higher rate for treatment 1, treatment 2, and treatment 3 compared to the other treatments.

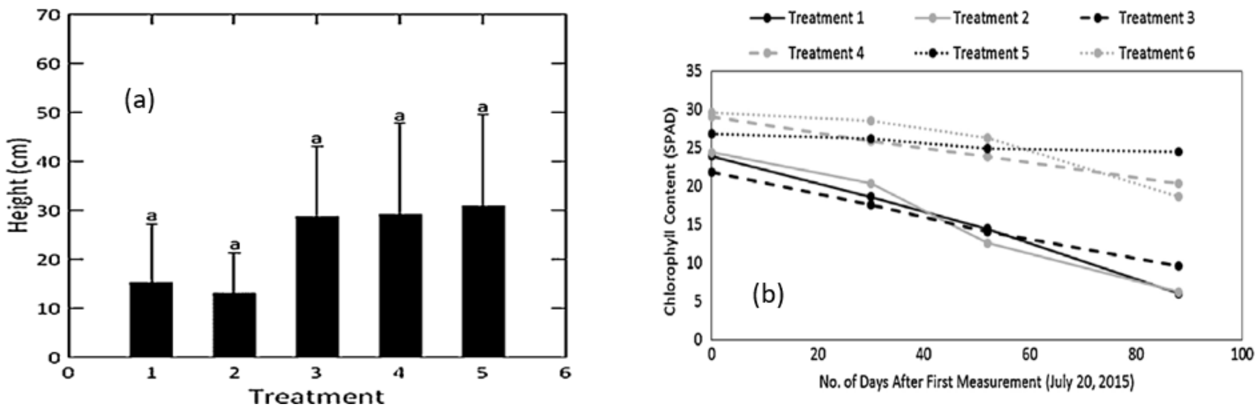


Figure 2.17 Effect of compost and organic amendments on (a) plant height, and (b) chlorophyll content. (McGrath and Henry 2016)

Treatment 1: Control, Treatment 2: 50% compost backfilled in tree pit, Treatment 3: Subsoil + Till, Treatment 4: 10% Organic Amendment, Treatment 5: 25% Organic Amendment, Treatment 6: 50% Organic Amendment

2.7 Chapter Conclusions

This literature review suggests that compost and proprietary soil amendments are effective in improving roadside vegetation growth by increasing soil nutrient uptake and moisture availability. Thus, they can be used in vegetation establishments along roadsides. Since chemical and physical properties of compost and soil amendments vary widely, and their effects on different plant species are different, extensive laboratory, greenhouse, and field testing should be conducted to prepare reliable design guidelines. The other variable that will affect vegetation improvement is the soil type. Topsoils are collected from local soil sources for roadside vegetation improvement projects which are likely to have different properties depending on their surrounding ecosystem.

Large scale field plots provide the most reliable methods to help understand the complex biocomplexities related to these projects. The literature also suggests that image analysis, plant height, root length and volume, trunk cross sectional area are some of the effective measurement options to quantify plant growth. By choosing the right product of compost and soil amendment with the most resistant plant species, and through proper construction in the field, healthy roadside vegetation is possible.

Chapter 3: Material Collection and Physicochemical Property Analyses

3.1 Laboratory Testing Methods

Four soil materials from Ortonville, Sanborn, Clearwater, and Glenwood and four different compost (yard waste, food waste, Grade 1, Biochar) materials were collected and analyzed to determine their corresponding index, physical, chemical, and biological properties. Bulk soil samples were collected by MnDOT personnel from field locations (Ortonville, Sanborn, Clearwater, Glenwood) and shipped to MSU's soil testing laboratory. Soil health analyses were conducted as a set of tests to determine soils' suitability for vegetation growth. These analyses also provide suggestions on soil management decisions. Table 3.1 summarizes the laboratory testing program. The following sections will briefly summarize the testing methods and their functionality corresponding to vegetation improvement.

3.1.1 Index Testing and Textural Classification

Soil index testing is performed to determine the engineering classification and texture of the soils. Soil is composed of a variety of mineral particles and the relative size distributions of those particles determines its texture. Soil texture determines the pore space or inter-aggregate spaces which affects water and gas movement in the soil. These in turn affect infiltration, permeability, leaching, and aeration characteristics of soils. For instance, clay particles have more surface area and will retain more water than sand. Hence, clay soils have a higher cation exchange capacity (CEC), a higher ability to retain nutrients, and sequester more organic materials than sandy soil (Moebius-Clune et al., 2016). Thus, soil texture can give a general idea of how the soil will perform to establish vegetation.

To determine the engineering classification of the soil samples, a set of tests were performed according to ASTM standards, such as sieve analysis (ASTM D 6913), fines content (wet sieving) (ASTM D 1140), hydrometer (ASTM D 422), and Atterberg limits test (ASTM D 4318) (Table 3.1). Sieve analysis was performed using sieves sized between 2 inches (50 mm) and U.S. #200 sieve (0.075 mm). In addition, wet sieving (for fines content) was performed to determine the amount of material finer than U.S. # 200 (0.075 mm) by washing the soil materials. To determine the size distribution of particles finer than the U.S. # 200 (0.075 mm), hydrometer tests were conducted on the materials passed through U.S. #10 (2 mm) sieve. Atterberg limit tests were performed to determine the liquid limit (LL), plastic limit (PL), and the plasticity index (PI) of soil materials. The wet preparation-multiple point test method was conducted on materials after they were sieved through the U.S. #40 (425 µm) sieve.

Food waste, yard waste, and biochar samples were analyzed using both sieve analysis and laser diffraction methods. 500 g of each material was subjected to dry sieving as described in the standard method AASHTO T-88 for particle size distribution. The fines (<0.003 inches) were analyzed using a SALD-2300 laser diffraction particle size analyzer. Laser diffraction works on the principles of light scattering from particles and can rapidly determine the sizes of clay and silt size particles. Results from the sieve analyses and laser diffraction were combined to construct the particle size distribution curves for composts and biochar materials. Soil textural analysis was performed by following the protocols described by Kettler et al. (2001). In this method, approximately 14 g soil passing the U.S. #10 (2 mm) sieve is added to a dispersing agent in a centrifuge tube and shaken vigorously for 2 hours. The entire contents of the centrifuge tube are then washed over a 0.002 in (0.053 mm) sieve on top of a plastic funnel above a 1L beaker. Sand particles are captured in the top of the 0.002 in (0.053 mm) sieve and silt and clay particles are collected in the beaker. Silt and clay particles are re-suspended by stirring and clay particles are decanted. The sand and the settled silt particles are then oven-dried at 105° C to a constant mass. The textural analysis follows the United States Department of Agriculture (USDA) classification system; it does not correspond to the particle sizes defined by ASTM. In USDA classification textural class is defined by the relative amounts of sand 0.002 to 0.08 inch (0.05 to 2 mm), silt 0.00008 to 0.002 inch (0.002 to 0.05 mm), and clay less than 0.00008 inch (<0.002mm). Any particles greater than U.S. #10 sieve (2 mm) are considered coarse aggregate and are not included in the textural class (e.g., clay loam, sandy loam). The differences between ASTM and USDA standards can result in reporting of different silt and clay contents of the soils.

Table 3-1 Soils and organic amendments laboratory testing summary

Test Type	Test Name	Testing Method	Testing Facility
Index Properties	Moisture Content	ASTM D2216	MSU/UMD
	Particle Size Analysis	ASTM D6913/AASHTO T88/Laser Diffraction/Kettler et al., 2001	
	Fines Content	ASTM D1140	
	Plasticity (Atterberg Limits)	ASTM D4318	
	Hydrometer	ASTM D422	
	Specific Gravity of Soil Solids	ASTM D854	
Physical Properties	Predicted Available Water Capacity	Random Forest Model	Cornell Soil Health Lab
	Aggregate Stability	Moebius et al. 2007	
Biological Properties	Organic Matter	ASTM D2974/Wang et al., 2011/Ji-Peng et al., 2013/Broadbent, 1965	
	ACE Protein Index	Wright and Upadhyaya, 1996	
	Soil Respiration	Zibilske, 1994	
	Active Carbon	Weil et al. 2003	
Chemical Properties	pH	Lignin pH robot	
	Soluble Salt Content	Rhoades, 1982	

Test Type	Test Name	Testing Method	Testing Facility
	Nutrient Analysis (Extractable Phosphorus, Extractable Potassium, Minor Elements)	Modified Morgan's Solution analyzed with ICP (inductively coupled plasma emission spectrometer)	

The sieve analyses and Atterberg limits were used to classify the materials. Materials were classified in accordance with the ASTM D 2487-11 "Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System (USCS))" and the ASTM D 3282-09 "Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes (AASHTO classification system)." Soil textural classifications were determined in accordance with the United States Department of Agriculture (USDA) soil classification system (Figure 3.1).

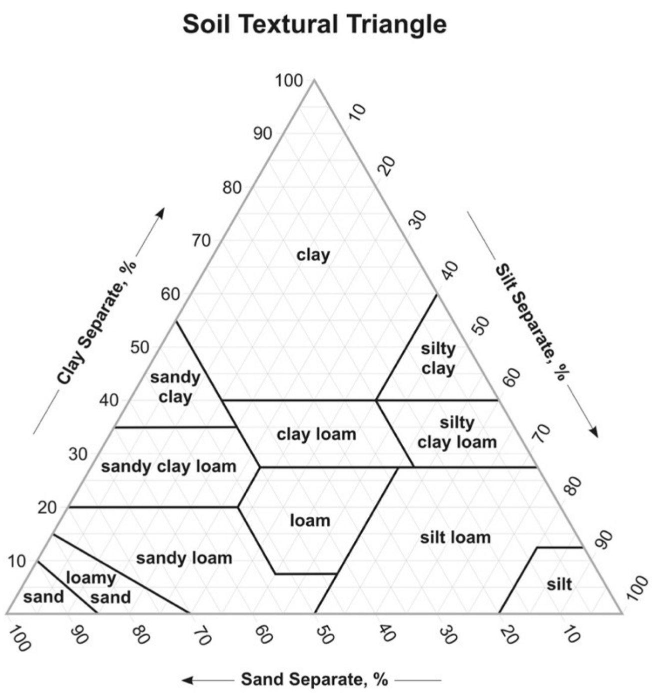


Figure 3.1 USDA soil classification triangle. (Source: NRCS/USDA)

3.1.2 Moisture Content and Specific Gravity Tests

The moisture content of the soil samples was determined according to ASTM D 2216-10, where a test specimen is over-dried at 110 ± 5°C to a constant mass. The loss of mass due to drying is the amount of water.

The specific gravity of a given material is defined as the ratio of the weight of a given volume of the material to the weight of an equal volume of distilled water. The specific gravity of soil solids was determined in accordance with ASTM D 854-98. Specific gravity was determined using a pycnometer with soil passing the U.S. #4 (4.75

mm) sieve. The specific gravity of soil is used to calculate soil phase relationships, and it is also used in the hydrometer analysis.

3.1.3 Predicted Available Water Capacity (PAWC)

Available water capacity (AWC) for plants is the difference between the water content at field capacity and permanent wilting point. Field capacity is the upper range of wetness when soil cannot hold any more water against gravity. The permanent wilting point is the lower end of the spectrum when only hygroscopic moisture, unavailable plant water, is left in the soil (Figure 3.2). AWC can be measured in a time-intensive laboratory experiment. Instead, Cornell Soil Health Lab uses a modeling-based approach to predict AWC from a set of measured sample parameters such as sand, silt, clay, organic matter, active carbon, ACE protein index, respiration, wet aggregate stability, and trace metal contents (Moebius-Clune et al., 2016). It uses a Random Forest model, a machine learning algorithm, to predict AWC from the above parameters.

PAWC is an indicator of plant-available water in the soil. Soils with fine textures and organic matter usually have higher AWC than sandy soils. Soils with lower PAWC face higher stresses in drought conditions. Thus, PAWC is a vital soil health indicator for plant and vegetation growth.

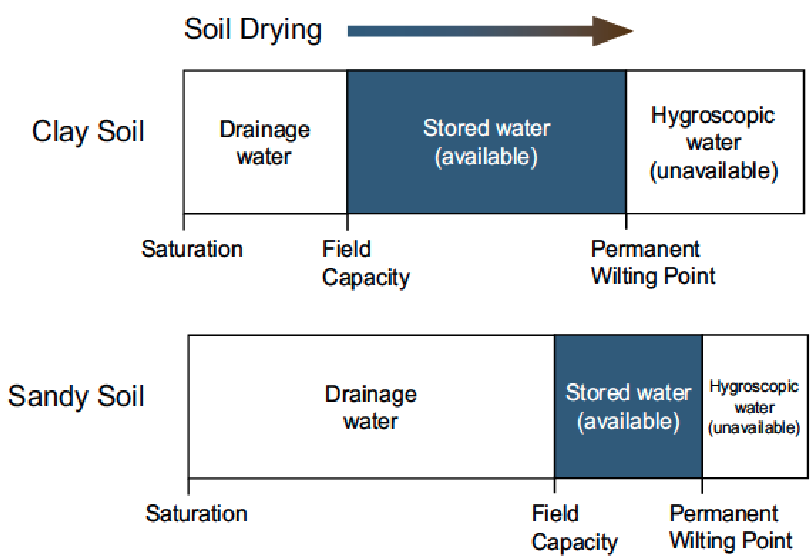


Figure 3.2 Water storage capacity of clay and sandy soils. (Moebius-Clune et al., 2016)

3.1.4 Aggregate Stability

Aggregate stability measures how soil particles hold together under a simulated rainfall event. A rainfall simulator is used to apply rain showers over sieves containing soil particles sized between 0.01 inch (0.25 mm) and 0.08 inch (50 mm). The rainfall simulator runs for 5 minutes, and it delivers approximately 0.5 inch (25 mm) water to the sieve (Figure 3.3). The unstable soil aggregates slake and pass through the sieves. The remaining aggregates on the sieve are considered stable (Moebius-Clune et al., 2016).

Aggregate stability is an important physical indicator of soil health. Soils with poor aggregate stability will have higher surface runoff, less infiltration, and higher erosion than soils with good aggregate stability. In addition, soil with low aggregate stability can reduce air exchange and seed germination, which are detrimental to vegetation growth. The addition of organic matter increases the aggregate stability of soils (Moebius-Clune et al., 2016).

Figure 3.3 (a) Aggregate stability test, (b) A rain-stimulator is used simulate rainfall. (Moebius-Clune et al., 2016)

3.1.5 Soil Organic Matter and Soil Organic Carbon

Soil organic matter (SOM) consists of living organisms, slightly altered plant and animal residues, and well-decomposed organic residues that can undergo further decomposition (Magdoff, 1992). Total carbon (TC) in soils is the sum of both organic (SOC) and inorganic carbon (SIC). SOC is found in organic matter as a fraction of total SOM, and SIC is mostly found in carbonate minerals. (Nelson and Sommers, 1996). SOC consists of approximately 58% of total SOM (Sikora and Stott, 1996). This constant (0.58) has been used to convert SOC from SOM (Wang et al., 2011).

Measurement of SOM varies slightly between different methods. Loss on ignition (LOI) is a standard method to determine SOM (Ball, 1964; David, 1988; De Vos et al., 2005). In general, a soil specimen is over-dried at 105°C at constant mass. The oven-dried sample is subjected to a very high temperature, ranging from 360 to 550°C, and the percent LOI is calculated based on the difference in over-dried mass. The LOI (360 to 550°C) represents the total SOM in soil. SOC value is determined by multiplying the LOI value with a 0.58 conversion factor.

Carbonates and gypsum can interfere with the accurate determination of SOC (Nelson and Sommers, 1996). It is recommended to determine the presence of carbonate in soils with diluted acid prior to SOC testing. On the other hand, it is also known that carbonates do not interfere with the LOI method between 360°C and 550°C temperature ranges (Sikora and Stott, 1996; Moebius-Clune et al., 2016). Soil SOM and SOC values were tested at both MSU and Cornell Soil Health Laboratory (CSHL) facilities. The following sections briefly describe the following testing procedures.

3.1.5.1 CSHL Test Procedure for SOM

CSHL measured LOI by heating a soil specimen at 500°C for 2 hours. SOM was calculated using equation-1 (Moebius-Clune et al., 2016).

$$\%SOM = \%LOI_{500°C} * 0.7 - 0.23 \qquad (1)$$

where *%SOM* is the percent soil organic matter, $\%LOI_{500°C}$ is the percent loss on ignition at 500°C temperature. CSHL reported that it measured total carbon (TC) values at 1100°C by complete oxidation of C to CO_2.

3.1.5.2 MSU Test Procedure for SOM and SOC

SOM was tested by MSU at 440°C for 2 hours using the LOI method, as described in equation-2 (ASTM D 2974). A conversion factor of 0.58 was used to calculate SOC values from SOM values as shown in equation-3 (Nelson and Sommer, 1996; Wang et al., 2011).

$$SOM_{440°C} = \left(\frac{W_{440°C} - W_{105°C}}{W_{105°C}}\right) * 100 \qquad (2)$$

where, $SOM_{440°C}$ is percent organic matter measured at 440°C, $W_{105°C}$ and $W_{440°C}$ are the soil weights after combustion at 105 and 440°C, respectively.

$$SOC_{440°C} = \left(\frac{W_{440°C} - W_{105°C}}{W_{105°C}}\right) * 0.58 * 100 \qquad (3)$$

where, $SOC_{440°C}$ is percent organic C measured at 440°C, $W_{105°C}$ and $W_{440°C}$ are the soil weights after combustion at 105 and 440°C, respectively.

3.1.5.3 Soil Inorganic Carbon

Soil inorganic carbon (SIC) mostly includes carbon from calcium carbonate ($CaCO_3$) and calcium magnesium carbonate ($CaMgCO_3$) in calcareous soils (Sherrod et al., 2002). Determination of soil inorganic carbon is essential for carbon sequestration (Lal, 2004). The LOI method at higher temperatures was used to determine SIC (Jia-Ping et al., 2013; Wang et al., 2011).

SIC was determined by modifying the method described by Jia-Peng et al. (2013). At first, an oven-dried (105°C) specimen is heated to 440°C to determine SOM. The soil specimen is then heated to 750°C for 2 hours. Percent soil inorganic carbon is calculated from the mass difference between dried soil samples at 440°C and 750°C (equation-4).

$$SIC_{750°C} = \left(\frac{W_{440°C} - W_{750°C}}{W_{105°C}}\right) * 0.273 * 100 \qquad (4)$$

where, $SIC_{750°C}$ is percent inorganic C measured at 750°C, $W_{105°C}$, $W_{440°C}$, $W_{750°C}$ *are the* soil weights after combustion at 105, 440, and 750°C, respectively. 0.273 is the conversion constant to convert the mass of CO_2 to the mass of C (i.e., 12/40) (Jia-Ping et al., 2013; Wang et al., 2011).

3.1.6 Autoclaved Citrate Extractable (ACE) Protein Index

The Autoclaved Citrate Extractable (ACE) protein index indicates the protein present in the soil organic matter. ACE protein index has been used as an indicator of mineralizable nitrogen (N) (Hurriso et al., 2018). Microbial activities transform organic N into plant-available N. Morrow et al. (2016) showed that mineralizable N is sensitive to tillage. The protein content is an overall health indicator of a soil's biological and chemical health (Moebius-Clune et al., 2016).

ACE protein index was measured following the methodology described by Wright and Upadhyaya, (1996). In this method, 3 g of soil are weighed into glass tubes with 24 mL of sodium citrate buffer solution at pH 7.0. The mixture is shaken for 5 minutes at 180 rpm. The tubes are autoclaved for 30min at 121°C and 15 psi (6.9 kPa) pressure. 2 mL of sterilized slurry is then centrifuged at *10,000 x gravity* in micro centrifuge tubes to remove soil particles. The extract is then analyzed in a standard colorimetric protein quantification assay to determine the total protein content by reading color developments. A spectrophotometric plate reader is used to scan the color of the samples (Figure 3.4 (Moebius-Clune et al., 2016).

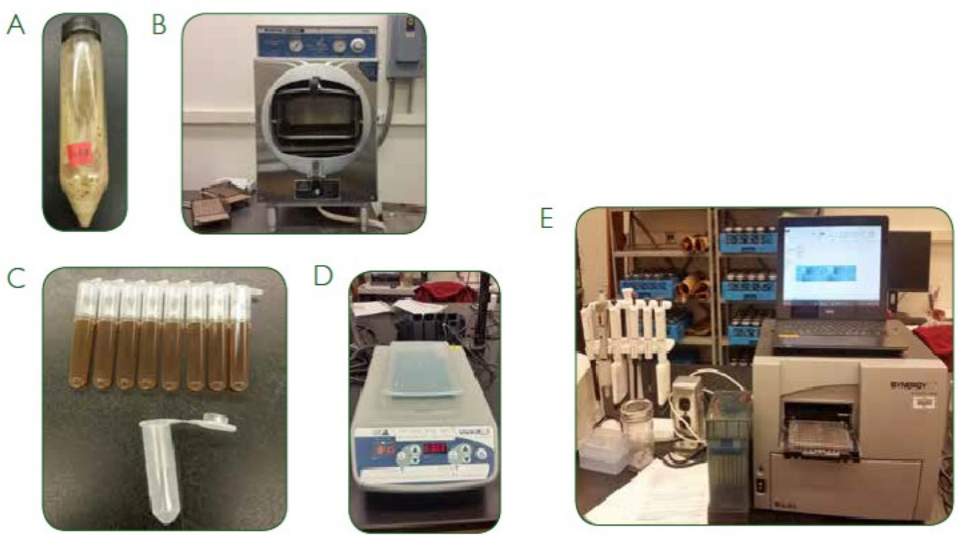


Figure 3.4 (a) Lab procedure for the ACE Protein Index, (b) glass tubes, (c) autoclave clarified extract, (d) protein assay, and (e) spectrophotometric plate reader. (Moebius-Clune et al., 2016)

3.1.7 Soil Respiration

Soil respiration test measures CO_2 produced by soil microorganisms. Under aerobic conditions, soil microorganisms decompose organic matter and release CO_2 into the atmosphere. Some standard laboratory techniques for soil respiration measurements are the alkali adsorption method (AA method), closed chamber method (CC method), dynamic closed chamber method (DC method), and open flow infra-red gas analyzer method (OF-method) (Bekku et al., 1997). An adapted procedure for the alkali adsorption method was followed as described by Zibilske, (1994). In this method, 20 g air-dried soil is weighed into an aluminum weighing board and placed over two filter papers inside a mason jar. CO_2 is measured using an alkaline solution (trap solution). Nine mL of 0.5 M KOH is placed inside the jar. 7 mL of distilled water is pipetted into the jar to wet the soil. The jar is sealed tightly and incubated for four days. After four days, the conductivity of the trapped solution is measured (Figure 3.5). Electrical conductivity decreases with an increase in CO_2 adsorption as OH^- concentration decreases and CO_3^{2-} concentration in the trap solution increases. The amount of respired CO_2 is calculated by comparing the conductivities of the trap solution with a saturated CO_2 solution (Moebius-Clune et al., 2016)

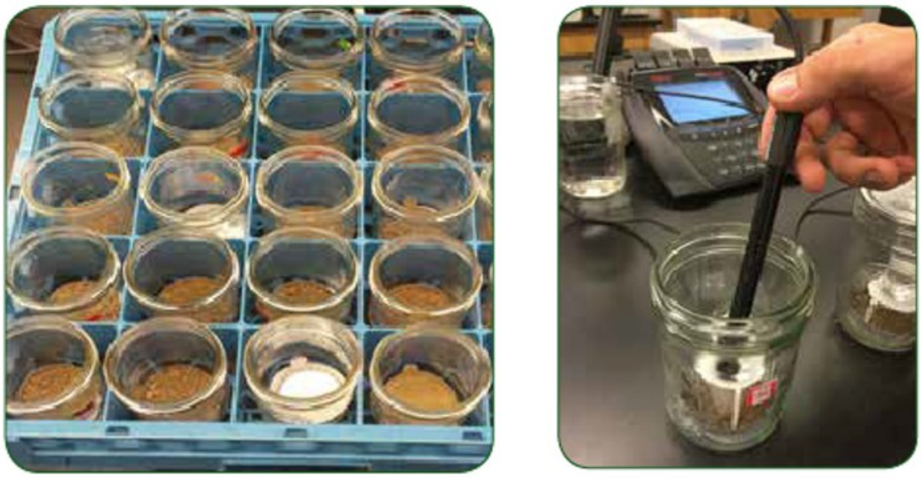


Figure 3.5 Soil respiration is determined by measuring electrical conductivity. (Moebius-Clune et al., 2016)

3.1.8 Active Carbon

Active carbon is a small percentage of total organic carbon in the soil that works as a readily available energy source for soil micro-organisms. Active carbon is positively correlated with organic matter, aggregate stability, respiration, and microbial biomass.

A procedure described by Weil et al. (2003) was followed to measure active carbon of materials. In this method, air-dried soil is mixed with a permanganate potassium solution ($KMnO_4$). The addition of $KMnO_4$ produces a deep pink color which gradually fades away as permanganate oxidizes the active carbon in the soil. The color change is measured using a spectrophotometer or colorimeter. The measured value from the colorimeter is then converted to active carbon in units of mg carbon per kg of soil (Moebius-Clune et al., 2016).

3.1.9 Soil pH

Soil pH is a measure of soil's acidity. For most crops, the optimum pH is around 6.2-6.8. Soil pH was measured by a pH electrode probe using a Lignin pH robot. A suspension of 2:1 ratio of water and soil is used to determine the pH (Moebius-Clune et al., 2016).

Soil pH can indirectly help to determine what nutrients are available to plants. Nutrients such as phosphorus, iron, manganese, copper, and boron become unavailable if pH (>8.5) is too high. If pH (<5) is too low, nutrients such as calcium, magnesium, phosphorus, potassium, and molybdenum become unavailable (Brady and Weil, 1999). Fierer and Jackson, (2006) reported that a pH ranges from 5.5 to 8.8 is required for microbial activities in soil. Christians et al. (2016) reported that plant essential nutrients are mostly found in the pH range of 6 to 7.

3.1.10 Soluble Salt Content

Excessive soluble salt can hinder plant growth. Soluble salts in soil are mostly from Mg^{2+}, Ca^{2+}, Na^{+}, K^{+}, Cl^{-}, SO_4^{2-}, and HCO_3^{-} ions. A common method to determine soluble salt content in soil is to conduct electrical conductivity (EC) measurements. The procedure described by Rhoades, (1982) was followed to determine the EC of materials. In this method, 20 mL distilled water is added to 20 mL of dried ground soil to make a 1:1 soil: water suspension by volume. The solution is settled in one hour. The EC of the solution is then measured with a calibrated conductivity meter. As the dissolved salts in the solution increase, EC increases. Thus, the presence of high soluble salt in the water result in higher EC (Moebius-Clune et al., 2016).

3.1.11 Nutrient Analysis

Estimating available macro and micronutrients is an integral part of soil health analysis. Nutrient availability is critical to plant production, and if sufficient nutrient is not available at the right time, plant growth can be hindered. In addition, excessive nutrient availability can be detrimental to plant growth and environmental degradation (Moebius-Clune et al., 2016).

Nitrogen (N), Phosphorus (P), and Potassium (K) are considered soil macronutrients, and iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and molybdenum (Mo) are considered soil micronutrients. Calcium (Ca), magnesium (Mg), and sulfur (S) are considered secondary elements. Usually, plant uptake of macronutrients is higher than micronutrients and minor elements. However, deficiency in minor elements can cause decreased crop yield (Moebius-Clune et al., 2016).

Availability of nutrients in the soil is measured with Modified Morgan's solution. Morgan's solution is ammonium acetate plus acetic acid buffered at pH 4.8. Soil is mixed with Morgan's solution, and the slurry is filtered through a filter paper. The filtrate is analyzed using an inductively coupled plasma emission spectrometer (ICP) to determine nutrients concentrations. As part of the soil health analysis, extractable phosphorus, extractable potassium, and minor elements (Mg, Fe, Mn, and Zn) are reported.

3.2 Soil Characterization

Four types of soil samples are collected for this project. They were collected from four different locations around Minnesota, as recommended by the project TAP. The following sections discuss their locations, and index, physical, biological, and chemical properties. The detailed soil health analysis results from Cornell Soil Health Lab (CSHL) are shown in Appendix A.

3.2.1 Soil Locations

Bulk soil samples were collected in 55-gallon drums from four different project locations in Minnesota. The locations of these soils are shown in Figure 3.6.

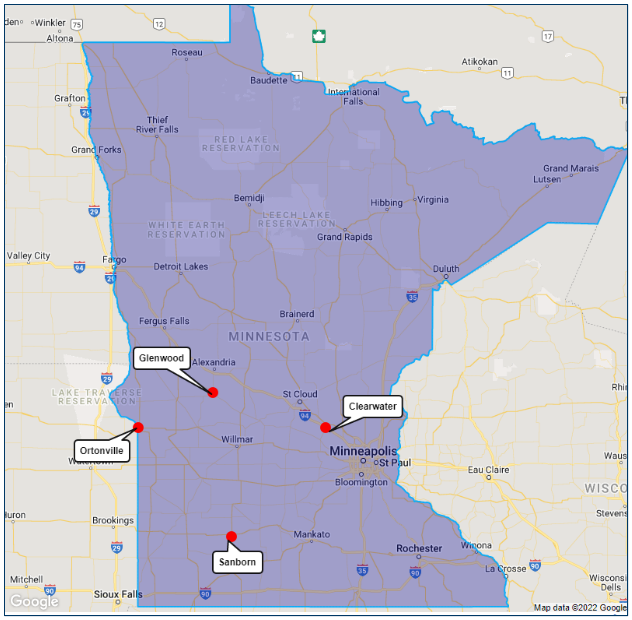


Figure 3.6 General locations of soil samples.

Ortonville (Figure 3.7a) and Glenwood (Figure 3.7b) samples were collected from topsoil stockpiles. Sanborn soil was collected from a roadway slope (Figure 3.7c). Clearwater soils were taken from the median of Interstate 94 near city of Monticello (Figure 3.7d). Ortonville soil was collected from a project located near the US 12 and 640 Ave intersection from city of Ortonville. Glenwood soil was taken from MnDOT project site "6106-25", adjacent to the MnDOT radio tower in city of Glenwood, MN along state highway 55. Clearwater soil samples were collected from the 'Interstate 94 third lane' project. Sanborn soil was collected from a MnDOT bridge project located near the intersection of US 71 and County Road 41 from the city named *Sanborn*. In this study, the names of the cities where the materials were collected have been used to label the soils. These labels do not refer to any geological classification or series.

Figure 3.7 Project Locations (a) Ortonville, (b) Glenwood, (c) Sanborn, and (d) Clearwater.

3.2.2 Soil Index Properties

Soil index properties are summarized in Table 3.2 along with their USCS, AASHTO, and USDA classifications. Sanborn, Clearwater, and Glenwood soils are classified as silty clayey sand (SC-SM) to silty sand (SM), and Ortonville soil is classified as lean clay (CL) according to USCS classification. The soils have fines content between 23% and 55%, and moisture content between 11% and 26%. High moisture content in Ortonville soil can be correlated to the high fines content of this soil, as finer particles generally hold more water than sand-sized particles. The soils are non-plastic to low plastic except the Ortonville soil which has a plasticity index of 15. The specific gravity of the soils ranges from 2.69 to 2.79. All the soils have very low gravel content (0 to 6%).

Particle size distribution curves of each soil are shown in Figure 3.8. Ortonville soil has approximately 21% clay particles, and Sanborn, Clearwater, and Glenwood have approximately 6% to 9% clay size particles. (Figure 3.8)

Table 3-2 Soil index properties

Soil	%Gravel	%Sand	%Fines	USCS	AASHTO	USDA	PI*	Specific Gravity
Ortonville	0	45	55	CL	A-6	Loam	15	2.69
Sanborn	6	66	29	SC-SM	A-2-4	Sandy Loam	7	2.74
Clearwater	3	74	23	SM	A-2-4	Sandy Loam	-	2.79
Glenwood	5	67	29	SM	A-2-4	Sandy Loam	-	2.78

**PI=Plasticity Index*

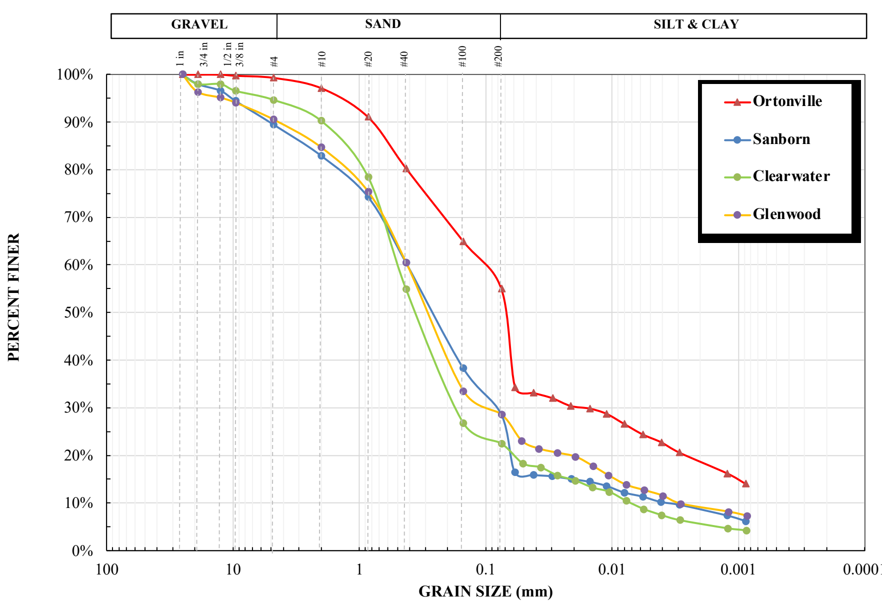


Figure 3.8 Particle size distribution curves of soils (Pamuru et al., 2024a).

3.2.3 Soil Physical Properties

3.2.3.1 Predicted Available Water Capacity (PAWC)

PAWC is predicted from a set of parameters using a Random Forest model. PAWC values of soil samples are presented as grams of water per gram of soil and summarized in Table 3.3. PAWC values of the soil samples range from 0.16 (Clearwater) to 0.24 (Ortonville). These values are given a rating based on similar results found on regional soils with similar textures. All the soils are rated in a high to very high functionality range (Moebius-Clune et al., 2016). Ortonville soil has the highest rating of 87 which corresponds to high organic matter (5.6%) and high clay content (21%). Organic matter increases water holding capacity in soils and increases cation exchange capacity. Clearwater soil has the lowest rating of 64, still in the high functionality range, which corresponds to high sand content (74%). Coarse textured soils retain less water than fine-textured soils. Based on the PAWC results, the soils have very good water capacity for vegetation growth, and any management decision (e.g., tillage, compaction) should aim at maintaining this functionality.

Table 3-3 Predicted available water capacity of soils

Soil	PAWC (gm/gm)	Rating
Ortonville	0.24	87
Sanborn	0.18	76
Clearwater	0.16	64
Glenwood	0.20	83

3.2.3.2 Aggregate Stability

Aggregate stability is a measure of how soil particles hold together under a rapid wetting event such as a thunderstorm. Aggregate stability values of soils are presented as percent (%) and summarized in Table 3.4. Aggregate values of the soil samples range between 8% (Ortonville) and 18% (Clearwater). These values are given a rating based on similar results found on regional soils with a similar texture. All the soils are rated in a very low to low functionality range (Moebius-Clune et al., 2016). This low rating is an indicator of high surface runoff and erosion potential during a storm event. Based on the aggregate stability results, any management decisions (e.g., compost addition, cover cropping) should focus on increasing the stability.

Table 3-4 Aggregate stability of soils

Soil	Aggregate Stability (%)	Rating
Ortonville	8	9
Sanborn	11	13
Clearwater	10	11
Glenwood	18	22

3.2.4 Soil Biological Properties

3.2.4.1 Soil Organic Matter

Soil organic matter, organic carbon, and inorganic carbon were measured using the LOI method. The percentages of organic matter, organic and inorganic carbon, and total carbon are shown in Figure 3.9. Ortonville soil has the highest organic matter (5.6%), and Sanborn and Glenwood soils have approximately 4% organic matter. High organic matter content in Ortonville soil can be correlated with high fines content, as organic materials have finer textures, and they tend to stick with soil particles.

Soil organic carbon ranges between 2% and 3%, with Ortonville soil having the highest organic carbon content. Sanborn, Glenwood, and Clearwater soils have similar organic carbon contents (1.9% - 2.4%). The inorganic carbon contents of the soils range between 0.3% and 0.9%. This low inorganic carbon content indicates that the concentration of carbonate materials is very low in the soils collected for this project. Total carbon values are the sum of organic and inorganic carbon contents. Average total organic carbon values range between 2.2% and 3.6% in the soils (Figure 3.9).

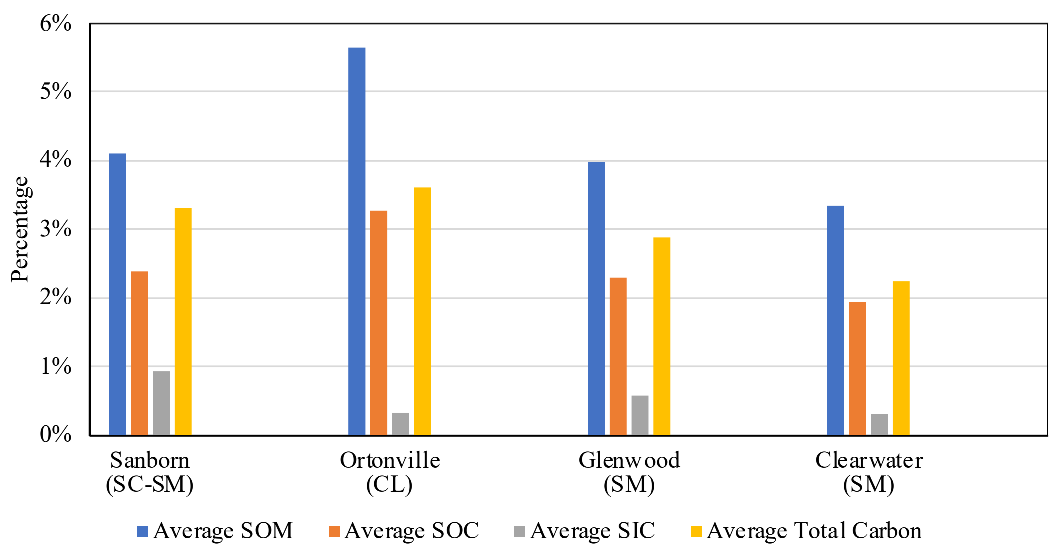


Figure 3.9 Soil organic matter, organic carbon, and inorganic carbon.

3.2.4.2 Autoclaved Citrate Extractable (ACE) Protein Index

ACE protein index is a measure of mineralizable N content in the SOM that can be made plant available by microbial activities. It is measured by extraction with citrate under high temperature and pressure. Protein index values of soil samples are summarized in Table 3.5. Protein index values are either 4 or 5. These values are given a rating based on similar results found on regional soils with a similar texture. All the soils are rated in the very low to low functionality range (Moebius-Clune et al., 2016). Based on the protein index values, the soils do not contain sufficient organically bound N that can readily be made plant available. Organically bound N is an important indicator of soil health. The addition of N based fertilizer can increase the protein index (Moebius-Clune et al., 2016).

Table 3-5 ACE protein index of soils

Soil	Protein Index	Rating
Ortonville	5.0	36
Sanborn	4.0	19
Clearwater	5.0	22
Glenwood	5.0	20

3.2.4.3 Soil Respiration

Soil respiration is an important indicator of biological activity in the soil and is a measure of the metabolic activity of the microbial community. Soil respiration values are presented as total CO_2 released (mg) per gram of soil and summarized in Table 3.6. Respiration values of the soil samples range from 0.4 mg/gm and 0.6 mg/gm. These values are given a rating based on similar results found on regional soils with a similar texture. All the soils obtained a low functionality rating except for the Sanborn soil which has a medium functionality rating (Moebius-Clune et al., 2016).

Based on the ratings, it can be concluded that soil respiration is functioning at a suboptimal level, which can hinder nutrient cycling, nitrogen transformation, and decomposition of organic residues. The addition of soil amendment, compost, and biochar products with light tillage application can increase the respiration of roadside soils. Study of these parameters is included in this research project.

Table 3-6 Respiration of soils

Soil	Respiration (mg/gm)	Rating
Ortonville	0.4	28
Sanborn	0.6	50
Clearwater	0.4	29
Glenwood	0.5	39

3.2.4.4 Active Carbon

Active carbon is a measure of a small percentage of SOM that is readily available as a food source for soil microbes. It is measured by potassium permanganate oxidation. Active carbon values of soil samples are presented in parts per million (ppm) and summarized in Table 3-7. Active carbon values of the soil samples range between 455 ppm and 598 ppm. These values are given a rating based on similar results found on regional soils with a similar texture. All the soils are rated in the high functionality range, except for Clearwater soil which has a medium functionality rating (Moebius-Clune et al., 2016). Based on the results, these soils have a good source of readily available foods for soil microbes and management should focus on maintaining this by providing compost, amendments, and organic matter.

Table 3-7 Active carbon values of soils

Soil	Active Carbon (ppm)	Rating
Ortonville	598	70
Sanborn	540	67
Clearwater	455	51
Glenwood	536	66

3.2.5 Soil Chemical Properties

3.2.5.1 Soil pH

Soil pH values are presented in standard pH units and summarized in Table 3.8. pH values of the soil samples range between 7.2 and 7.7. The soils are rated in the high to very high functionality range (Moebius-Clune et al., 2016), which means that soil pH is at an optimal level for plant growth. Christians et al., (2016) reported that plant essential nutrients are mostly found in the soil pH range of 6 to 7.

Table 3-8 pH Value of Soil Samples

Soil	pH	Rating
Ortonville	7.2	100
Sanborn	7.7	73
Clearwater	7.4	96
Glenwood	7.5	93

3.2.5.2 Soluble Salt Content

Different plants respond differently to the soluble salt concentrations in the soils. In general, salinity increases the osmotic potential of soil water relative to plant water, thereby making it difficult for plants to uptake water from the soil even if enough water is present. High salt content (e.g., Na^+) can be toxic to some plants. Na^+ ions can also exchange Ca^{++} and Mg^{++} ions from the soil mineral structure, thereby deteriorating the soil's ability to retain mineral structure (Moebius-Clune et al., 2016). Soluble salt content values are summarized in Table 3.9. The degree of salinity values is taken from Dahnke and Whitney, (1988). All the soils have negligible salt content, indicating that soluble salt contents in the soil are at an optimum level.

Table 3-9 Soluble salt contents

Soil	Salt Content (mmho/cm)	Degree of Salinity
Ortonville	0.21	Non-Saline
Sanborn	0.14	Non-Saline
Clearwater	0.28	Non-Saline
Glenwood	0.34	Non-Saline

3.2.5.3 Extractable Phosphorus

Phosphorus (P) is one of the essential macronutrients in soil. Extractable phosphorus is a measure of phosphorus availability to plants. It is measured using modified Morgan's solution using an ICP spectrometer. Phosphorus values of the soils are presented in parts per million (ppm) units and summarized in Table 3.10. Extractable phosphorus values of the soil samples range between 5 ppm and 12 ppm. These values are given a rating based on an optimality curve. The soils are rated between medium and very high functionality (Moebius-Clune et al., 2016). Ortonville, Sanborn, and Clearwater soil have very high functionality which means soil is at an optimum level in terms of phosphorus availability. Glenwood soil has a medium functionality; hence fertilizer/amendment products may be added to increase phosphorus availability. Christians et al. (2016) recommended 2 lb./1000 ft^2 (10 gm/m^2) phosphorus fertilizer for seed germination if available P values are less than 10 ppm in soils.

Table 3-10 Extractable phosphorus values of soils

Soil	P (ppm)	Rating
Ortonville	5.0	100
Sanborn	7.0	100
Clearwater	5.0	100
Glenwood	2.0	49

3.2.5.4 Extractable Potassium

Potassium (K) is another essential macronutrient in soil. Extractable potassium is a measure of potassium availability to plants. It is measured using modified Morgan's solution using an ICP Spectrometer. Extractable potassium values of soil samples are presented in parts per million (ppm) units and summarized in Table 3.11. Extractable potassium values of the soil samples range between 50 ppm and 139 ppm. These values are given a rating based on an optimality curve. The soils are rated from high to very high functionality (Moebius-Clune et al., 2016), which means the soils of this project are performing at an optimum level in terms of potassium availability. However, potassium is easily leached from sandy soil, and organic matter addition does not readily improve potassium availability (Moebius-Clune et al., 2016). Therefore, it is important to monitor potassium levels in soils and provide the optimum level of K through fertilizer and amendments. Christians et al. (2016) recommended 2 lb./1000 ft^2 (10 gm/m^2) potassium (K_2O) fertilizer for non-trafficked turf grass establishment if K level in the soil is in the range of 51-75 ppm.

Table 3-11 Extractable potassium values of soils

Soil	K (ppm)	Rating
Ortonville	139.0	100
Sanborn	79.0	100
Clearwater	50.0	74
Glenwood	61.0	86

3.2.5.5 Minor Elements

Minor elements are also essential to plant nutrients and contain both soil micronutrients (Fe, Mn, Zn, Cu, B, Mo) and secondary nutrients (Ca, Mg, S). Minor elements affect crop yield and quality. They can also cause toxicity if present in too high concentrations. Mg, Fe, Mn, and Zn are measured using modified Morgan's solution using an ICP Spectrometer. Minor element concentrations in soil samples are presented in parts per million (ppm) units and summarized in Table 3.12. Mg values of the soil samples range between 214 ppm and 634 ppm, with Ortonville soil having the highest concentration. Fe values range from 0.1 ppm to 0.6 ppm. Mn is present in the range from 3 ppm to 12.4 ppm, and Zn concentrations are between 0.2 ppm and 1.3 ppm. These values are given a rating based on an optimality curve. Three soils are rated as very high functionality; Glenwood soil has a medium functionality rating (Moebius-Clune et al., 2016). Glenwood soil has a Zn concentration of 0.2 ppm, which is considered deficient.

Table 3-12 Minor element values of soils

Soil	Mg (ppm)	Fe (ppm)	Mn (ppm)	Zn (ppm)	Rating
Ortonville	634	0.1	4	0.4	100
Sanborn	256	0.6	12.4	1.3	100
Clearwater	214	0.1	3	2	100
Glenwood	411	0.4	8	0.2	56

3.3 Compost and Biochar Characterization

When added to soil, compost and biochar materials are expected to improve the soil's physical, biological, and chemical properties. Compost is a nutrient-rich amendment derived from organic materials. Biochar is a substance that looks like charcoal and is produced from thermal treatment of biomass in a controlled process called pyrolysis. Black Carbon (BC) is the main component of biochar, and it is produced by incomplete combustion of organic materials (Goldberg, 1985; Schmidt et al., 1999).

Compost products were collected from commercial compost manufacturers that meet the United States Composting Council's Seal of Testing Assurance Program (STA), which assures that compost product is fully processed. Biochar product was collected from an "International Biochar Initiative" certified manufacturer, which ensures that biochar does not contain any elements that can harm soil or the ecosystem.

3.3.1 Compost and Biochar Particle Size Analysis

Compost and biochar samples were analyzed using dry sieving and laser diffraction methods. Coarse fractions (> U.S. #200 sieve) were analyzed using sieves, and the fines fractions (< U.S. #200 sieve) were analyzed using a SALD-2300 laser diffraction particle size analyzer. Particle size distribution curves for compost and biochar are shown in Figure 3.10. From Figure 3.10, it is seen that compost and biochar materials are mainly composed of particles ranging in size between 0.08 in (U.S. #10 sieve) and 0.003 in (U.S. #200 sieve).

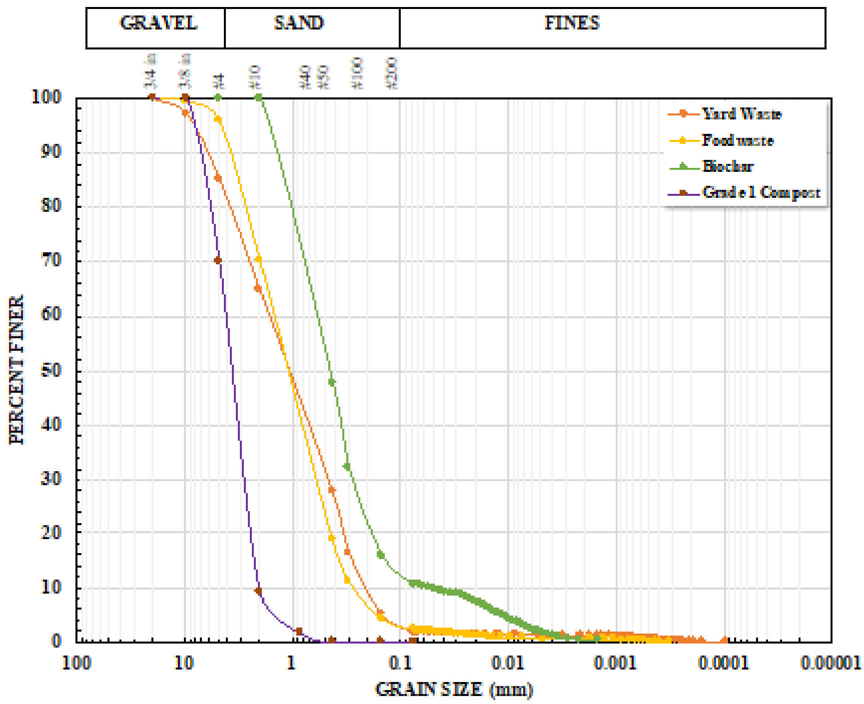


Figure 3.10 Particle size distributions of composts and biochar.

3.3.2 Compost and Biochar Health Analysis

Compost materials are good sources of organic matter, phosphorus, and potassium. When added to soil, compost decreases the soil's bulk density and increases cation exchange capacity and microbial activity (Farrell & Jones, 2009; Gao et al., 2010). Physical, chemical, and biological properties of food waste, yard waste, Grade 1 Compost, and one biochar sample were determined.

All the physical, biological, and chemical properties measured have very high ratings (80-100), which means that the materials are expected to be highly functional in crop growth. However, the rating system used is designed for soil material only, and the rating is based on an observed distribution in regional soils with a similar texture. As a result, the rating system may not be directly applicable for defining the functionality of compost and biochar materials. Therefore, the discussions hereafter will be focused only on relevant properties and measured values. The detailed analysis results of compost and biochar material are presented in Appendix B.

Table 3.13 summarizes the compost and biochar properties. Aggregate stability values of the compost and biochar range between 79% and 96% (Table 3.13). When added to soil, compost improves soil structure by binding between organic matter and clay particles via cation bridges and by stimulating microbial activity, root development, and plant growth (Farrell & Jones, 2009). The high aggregate values indicate that compost and biochar incorporation decrease surface runoff and erosion and facilitate aeration, infiltration, and water storage (Moebius-Clune et al., 2016).

As per Minnesota Department of Transportation (MnDOT) specifications, compost material should have more than 30% organic matter content (dry weight). Khater, (2015) reported 28.6% to 41.20% organic matter in composts from cattle manure, herbal plans residue, and sugar cane plants. According to Table 3.13, yard-waste and food-waste compost have 21% and 24% organic matter, respectively, lower than the MnDOT specification. Biochar and Grade 1 compost have 54% and 40% organic matter, respectively, higher than the MnDOT specification.

From Table 3.13, biochar material has the lowest protein index (0.3) compared to the composts. The protein index represents the organically bound N in SOM that microbial activity can mineralize for plant uptake (Moebius-Clune et al., 2016). One way to increase available N is to use biochar-based controlled-release nitrogen fertilizers (BCRNFs) or mix biochar with traditional N fertilizers such as urea or ammonium nitrate (Liu et al., 2019; Ullah et al., 2020).

Respiration measures soil microbial activity and is calculated by capturing and quantifying CO_2. Respiration values of the composts are between 2 mg/gm and 3 mg/gm, and the biochar is 1 mg/gm (Table 3.13). These values indicate high microbial activities in the media. Soil respiration has been strongly correlated with total soil C loss (Hansen et al., 2000). It is known that fertilization with compost can increase soil respiration and significantly increase CO_2 production (Lai et al., 2017). Hence, the respiration rate should be monitored to identify any potential adverse effects.

From Table 3.13, Active carbon in compost and biochar samples ranges from 979 ppm to 1427 ppm. These values indicate a very high available C concentration, which benefits the soil microbial communities.

According to MnDOT standard specifications (2020), compost materials should have a pH between 5.5 and 8. All the composts tested resulted in pH values ranging between 6.5 and 7.6 (Table 3.13), which indicates that composts are at acceptable pH values. The biochar material has a pH of 9.0; maximum achievable pH values for biochar are in the range of 10 to 12 for pyrolysis temperatures above 500°C. This high pH value is a result of increased carbonization (Weber and Quicker, 2016).

The soluble salt content values are summarized in Table 3.13 and indicate non-saline conditions for all the compost and biochar materials, except for food-waste compost which is moderately saline (5 mmho/cm) (Dahnke and Whitney, 1988). Salinity can affect the water uptake by plants. According to Richard (2012), the most sensitive plants can tolerate salinity less than 4 mmho/cm (ds/m). MnDOT standard specifications require compost to have salinity levels less than 10 mmho/cm. Native grass species are more stress-tolerant and should not be affected by these salinity levels (Paudel & Sun, 2023).

The P and K values of Grade 1 compost (animal manure) are 4,841 ppm (4.8 g/kg) and 22,484 ppm (22.5 g/kg), respectively. P and K values for yard-waste compost are 573 (0.6 g/kg) and 4,573 ppm (4.6 g/kg), respectively. These are lower than P and K concentrations reported by Richard (2012) for livestock manure and yard-waste composts. Food-waste compost has similar P and K values as yard-waste compost. Biochar has P and K values of 599 ppm and 3128 ppm, respectively.

Table 3-13 Physical, biological, and chemical properties of the compost and biochar materials

Property	Physical Properties	Biological Properties				Chemical Properties			
Material	Aggregate Stability (%)	Organic Matter (%)	ACE Protein Index	Respiration (mg/g)	Active C (ppm)	pH	Soluble Salt (mmho/cm)	Phosphorus ppm (g/kg^{-1})	Potassium ppm (g/kg^{-1})
Compost Grade 1	96	40	85	2	979	6.5	1.7	4841 (4.8)	22484 (22.5)
Yard-waste Compost	79	21	34	2	1427	7.3	2.3	573 (0.6)	4573 (4.6)
Food-waste Compost	90	24	63	3	1382	7.6	5.0	650 (0.7)	6301 (6.3)
Biochar	94	54	0.3	1	1396	9.0	1.1	599 (0.6)	3128 (3.1)

3.4 Chapter Conclusions

Soil health analysis reports indicate that micronutrients (P, K) are present at an optimum level, organic matter is present at an optimum level compared to similar textured soils, and available water capacity is also at a reasonably good level. Despite these positive indicators, improvements are possible. All the soils showed poor performance in aggregate stability measurement. Aggregate stability measures a soil's performance in erosion control and surface water runoff. One of the main aspects of roadside management is controlling erosion and decreasing surface water runoff. Poor aggregate stability can lead to higher erosion and surface water runoff. This concern can be addressed by improving vegetation growth. The current project aims to establish roadside grasses and forbs of native species. Post-vegetation aggregate stability of soil materials works as an important indicator of improvement. In addition, ACE soil protein index values of the soil samples were found to be in the low to medium functionality range. The addition of biomass such as organic matter, and N-based amendments can improve the protein index.

Compost and biochar materials are rich in organic matter and micronutrients. When added to soil, they will increase the soil's microbial activities. Health analysis results indicate that these materials are very high in organic matter and micronutrients. Studies have shown that the addition of compost and biochar improves vegetation growth; however, roadside vegetation establishment using these products needs careful consideration of their application rates. Even though high nutrient capacity is beneficial for plant growth, nutrients can be an environmental concern if leached and are transported to surface and ground water. Hence, it is important to measure the leaching potential of these materials.

Soil and compost health analysis results provided good indicators of the status of their physical, chemical, and biological properties. This knowledge will be beneficial in designing the greenhouse and mesocosm studies for this project and selecting optimum application rates for field studies. These results work as a baseline assessment and can be compared with post-construction status in the future.

Chapter 4: Greenhouse Pot Study

4.1 Overview

Roadside vegetation is crucial in controlling erosion, managing stormwater, and improving soil stability. However, post-construction soils often suffer from compaction, low fertility, and poor structure, making vegetation establishment challenging. Traditional approaches using topsoil and fertilizers are costly and lack standardized guidelines for optimal performance. A greenhouse pot study explores using organic amendments (OAs), such as compost and biochar, alongside proprietary amendments (PAs) with specific nutrient compositions, as alternatives for improving soil quality and promoting vegetation growth.

The research evaluates how different amendments influence soil properties, water retention, and plant growth. Compost has been shown to enhance soil fertility, microbial activity, and water infiltration, while biochar improves porosity and nutrient retention. Proprietary amendments, formulated to target specific deficiencies, support plant productivity by enhancing nutrient availability. Despite their potential, the effectiveness of these amendments depends on their composition, application rates, and compatibility with soil conditions.

The pot study aims to determine the optimal combinations of soil and amendment blends to promote vegetation growth and improve soil health. Greenhouse pot studies conducted at the University of Maryland (UMD) and Michigan State University (MSU) tested OAs and PAs under controlled environmental conditions. These experiments assessed the physical, chemical, and biological properties of the soils, along with plant biomass and coverage, to identify blends that meet the nutrient demands of rapid vegetation establishment. The findings will contribute to cost-effective solutions for post-construction soil remediation and vegetation management.

4.2 Soils and Amendments

The greenhouse pot study was conducted to evaluate the impact of organic amendments (OAs) and proprietary amendments (PAs) on improving poor-quality topsoils and providing rapid vegetation establishment. Four soil types, including three sandy loams from Glenwood, Sanborn, and Clearwater and one clayey soil from Ortonville, were used in the pot study. Table 3.2 shows the grain size distributions (ASTM D 6913, ASTM D 1140, ASTM D 422) and the physical characteristics of each material. OAs tested included yard waste (YW), food waste (FW), turkey litter and green waste-based Grade 1 (TL) composts, and wood-derived biochar (B). PAs investigated featured Sustane 4-6-4, Biotic, Carbogrow 3-0-3, and Kickstand DG, an iron-based amendment, applied at varying nutrient (NPK) rates. The study examined soil physical and chemical properties, plant growth, and biomass to assess the effectiveness of the amendments in enhancing vegetation establishment and soil quality.

4.2.1 Chemical Analysis of Soils and Amendment Blends

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 4.1 shows the analyzed soil properties and related test method information. Tables 4.2 and 4.3 present the summary of the chemical properties of the PAs and OAs, respectively.

Table 4-1 Soil analyses, methods, instruments, and detection limits

Soil Property	Units	Method	Instrument	Detection Limit
pH		ASTM D4972	VWR symphony B40PCID	-2
EC	mS/cm		VWR symphony B40PCID	0.001 mS/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%
NO_3-N, NH_4-N	ppm	KCl extraction	SEAL AQ300 Discrete Analyzer	0.01 ppm
TP	mg/L	Mehlich-3 extraction	Shimadzu Model ICPE-9820	0.1 mg/L

EC: Electrical conductivity, OM: Organic matter, LOI: Loss on ignition, TC: Total carbon, TN: Total nitrogen, TP: Total phosphorus

Table 4-2 Chemical analyses of proprietary amendments (PA)

Property	Carbogrow 3-0-3	Kickstand DG	Sustane 4-6-4	Biotic
pH	7.4	3.5	6.5	6.4
TN (%)	4.55	1.18	4.48	2.31
P (ppm)	739	10	2360	1022
K (ppm)	14832	13	21410	6004
Mg (ppm)	1266	19	928	566
Fe (ppm)	45	540	150	69

Table 4-3 Chemical analyses of the study soils and organic amendments (OA)

Property	Clearwater	Glenwood	Ortonville	Sanborn	Biochar	Grade 1 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 (ms/cm)	453 ± 10.7	335 ± 37	313 ± 46.4	197 ± 3.5	801 ± 46	15200 ± 440	4730 ± 236	3040 ± 219
OM%	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
P (mg-P/kg)	54.2 ± 0.44	32.4 ± 1.16	45.3 ± 0.47	26.6 ± 1.13	657 ± 7.65	3899 ± 256	655 ± 68.9	662 ± 48.9

Note: 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.

4.2.2 Amendment Application Rates

OAs were applied to the soils as a function of the OM content, whereas PAs were applied at increasing application rates of the nutrients. Table 4.4 and Table 4.5 show the three chosen application rates (designated as A, B, C) for OAs and PAs used as soil amendments, respectively.

MnDOT *Standard Specifications for Construction* lists criteria for topsoil materials to be used in stormwater control measures (SCM). One of the criteria for topsoil is the OM content, which needs to be between 3% and 15% (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 the three soils, with the exception of the Ortonville soil. Ortonville soil has an average OM content of 5.39% so the application rates target blends to reach 7.5%, 10% and 13% OM. For PAs, the MnDOT specifications manual states the use of manufacturer's recommended fertilizer rate for topsoil materials. Of the three application rates in Table 5, rate B was the prescribed value (manufacturers recommended rate for each product), and this was different for each PA. To investigate the effects of PA content under low and high nutrient conditions, rate A was selected to be half the recommended value (rate B), whereas rate C was twice rate B.

Table 4-4 Target organic matter (OM) rates of Soil-OA blends

Soil-PA Blends	Rate A (g/ft^2)	Rate B (g/ft^2)	Rate C (g/ft^2)
Glenwood-OA			
Sanborn-OA	**5%**	7.5%	10%
Clearwater-OA			
Ortonville-OA	**7.5%**	10%	13%

Table 4-5 The application rates of proprietary amendments (PA)

Soil-PA Blends	Rate A (g/ft^2)	Rate B (g/ft^2)	Rate C (g/ft^2)
Carbo-Grow 3-0-3	9.07	18.14	36.29
Kickstand DG + Fe Greens Grade	0.91	1.81	3.63
Sustane 4-6-4	11.34	22.68	45.36
Biotic Soil Amendment	21.00	42.00	84.00

4.3 Pot Experiments

A total of 156 (10-inch in diameter) pots (4 controls + 4 soils x 4 OAs x 3 OA rates, prepared in triplicates) were assembled in the UMD greenhouse complex. Similarly, another set of 156 pots (4 controls + 4 soils x 4 PAs x 3 PA rates, prepared in triplicates), were prepared in the MSU greenhouse facility. All blends were prepared in triplicates for testing reproducibility. Each pot contained two layers of a 2-inch (5.1 cm) subsoil (or compacted) layer at the bottom and a 4-inch (10.2 cm) fertile layer on the top (Figure 4.1). The subsoil layer was the 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. Figure 4.1 shows the schematic design of a pot with two soil layers.

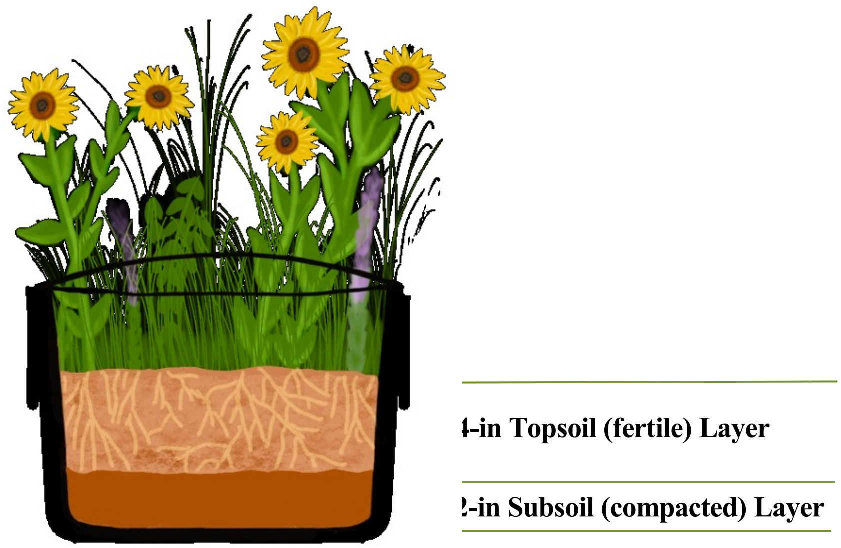


Figure 4.1 Schematic representation of a pot with soil layers (Pamuru et al.,2024a).

4.3.1 Pot Preparation

Plant debris (roots) and rocks (>1 inch) were separated from the soils to the extent feasible before placing the soil in the pot. Subsoil was placed and compacted into the pot at an amount that corresponds to its maximum dry density for a 2-inch depth. Maximum dry density of soils (Table 4.6) was determined by following the standard proctor procedure (ASTM D698). The second layer is topsoil (fertile layer), 4 inches in height, corresponding to the minimum depth in MnDOT Spec 3877 *Common Topsoil Borrow*. For the 4-inch 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.

Table 4-6 Soil compaction properties along with the corresponding bulk densities and organic matter contents for each soil/OA mixture.

Soil/OA		**Subsoil Layer**		**Topsoil Layer**	
		Maximum Dry Density (g/cm³)	***Optimum Water Content (%)***	***Bulk Density (g/cm³)***	***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

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. A 4-inch depth from the subsoil layer was marked, and the soil was scooped into the pot and uniformly distributed up to the 4-inch mark. The weight of the topsoil (top 4 inches fertile layer) was calculated in grams and divided by the volume of the pot for a 4-inch depth (i.e., 314.16 in^3 or 5148 cm^3) to compute the bulk density of the soil. This bulk density, along with the OM contents of soil and OA (Table 8), were used to estimate the amounts of soil and OA required for the specific OM target (Eq. 1). The blend volume ($V_{OA} + V_S$) in a pot diameter of 10 inches at a blend depth of 4 inches, is estimated to be 314.16 in^3 (5148 cm^3). Using these parameters in equation 4, the ratio of volume of OA to soil was calculated for a given OA application rate.

$$\frac{V_{OA}}{V_s} = \frac{\rho_s(\theta_t - \theta_s)}{\rho_{OA}(\theta_{OA} - \theta_t)} \qquad (4)$$

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

Mixing Proprietary Amendments: The soil bulk density from Table 4.6 was used to determine the amount of each soil needed for the topsoil layer. Unlike the procedure adopted for mixing OAs where the volumes of soil and OA change with application rates, when mixing PAs, the soil density was kept constant across all the pots for the same soil. The amount of each PA was estimated from the chosen additive rates (Table 4.5) and mixed uniformly into the topsoils.

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 4.1 g/m^2 (36.5 lb/acre), equivalent to 0.21 grams of seed mix per pot, of native Seed Mix 35-241 provided by MnDOT 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 Table 2.3; therefore, given the small amount (0.21 grams) of seed mix that was added, each pot may not have each seed type uniformly applied.

4.3.2 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 (81 °F) to 35 °C (95 °F) during the growing season, while cool-season grasses can thrive in temperatures between 18 °C (64 °F) to 24 °C (75 °F). Thus, throughout the experiment, the inside temperature of the greenhouse rooms was maintained at 23 °C (73.4 °F) to 25 °C (77 °F) during daytime and 17°C (63 °F) to 19 °C (66 °F) at night, with a 14-hr photoperiod. Watering events occurred three times a week and the amount corresponded to Minnesota's annual average precipitation rate of 32 inches. Additional water was supplemented on certain days in case plants and soil in the pots seem very dry. Snapshots of the greenhouse pot study experiments at UMD and MSU are presented in Figure 4.2.

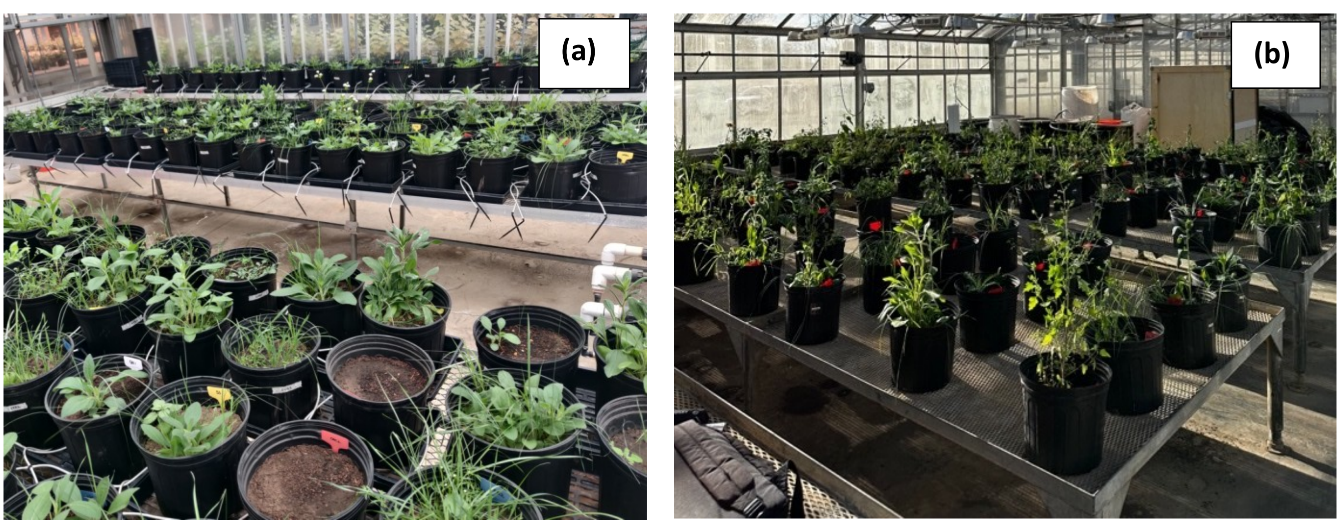


Figure 4.2 Pot setups. (a) in the UMD, and (b) MSU greenhouse facilities.

4.3.3 Pot Study Growth Measurements

Green Coverage: The pot experiment spanned 15 weeks (105 days) after seeding, from Aug 23 to Dec 6, 2022, at UMD and Oct 4, 2022, to Jan 17, 2023, at MSU. Images of the pots were captured bi-weekly, starting from week 3 until week 15, in a custom-built image station to ensure consistent lighting conditions (Figure 4.3). The image station setup consists of a beam that can move up and down, and a camera track slider that allows the camera to move horizontally. Both the beam and camera track slider are attached to a vertical track slider, which enables the movement of the beam, and the camera simultaneously as needed. Additionally, LED lights provided the required lighting to capture good quality images (Figure 4.3).

To analyze the images for percentage 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 feeding the original images (Figure 4.4a) as input to *Canopeo*, the images were preprocessed in Adobe Photoshop 2022, where the images were cropped along the inner diameter of the pot (Figure 4.4b) and then as an inscribed square that measures the same edge as the pot diameter. Since the black-eyed Susan plant species produce yellow blooming flowers, they were manually painted green (Figure 4.4c) as *Canopeo* does not read yellow color (which could yield underestimation of the %GC, Figure 4.4d). Figure 4.4 shows the image processing steps that were followed for estimating %GC.

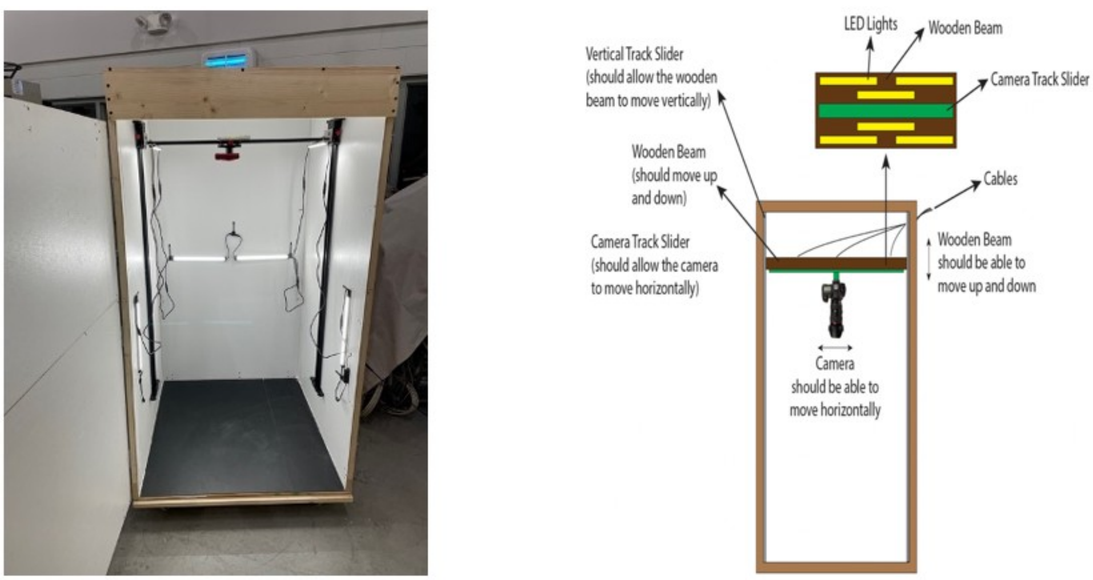


Figure 4.3 Image station setup in the MSU greenhouse facility (Pamuru et al., 2024a).

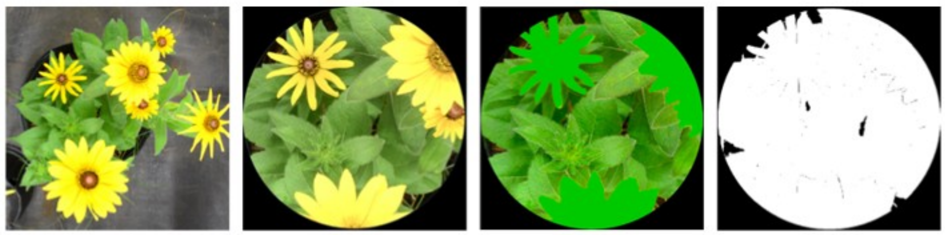


Figure 4.4 Image processing steps followed for %GC analysis (Pamuru et al., 2024a).

Destructive Growth Measurements: Several types of end-of-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 next to grasses in the pots. In addition, different amendments had different influences on the morphology of the BES plants. This prompted us to examine the BES plants to a greater degree in this study. Growth Index (GI) is a three-dimensional comprehensive parameter that is estimated by taking the average of the widest width (x), perpendicular width (y), and height (z) of a BES plant (Norcini and Aldrich 2003, Eq. 2).

$$GI = \frac{x+y+z}{3} \qquad (2)$$

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 (Figure 4.5). 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 a LI-3100C Area Meter. Snipped leaves of the healthiest BES plant per pot were spread on the conveyer belt of the instrument, which then rotates to scan the *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, transferring the shoots into brown paper bags and oven-drying at 50 °C (122 °F). for 48 hours. After drying, the plant material was weighed to report *dry plant biomass* (USDA NRCS 2022).

Figure 4.5 Differences in color, length, and leaf area of black-eyed Susan plants between soil blended with Grade 1 turkey litter compost (left pot) vs soil blended with biochar (right pot) (Pamuru et al., 2024a).

4.4 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 between two treatment groups or application rates. Linear correlations were noted; a regression analysis was carried out at alpha = 0.05 to determine the probabilistic significance (P) value.

4.5 Results and Discussion

4.5.1 Green Coverage

Figure 4.6 and Figure 4.7 demonstrate the final mean vegetation coverage (%GC) from week 15 (105 days after seeding) and temporal %GC patterns of the prairie mix for the various soils and their OA blends. Figure 4.8 and Figure 4.9 represent the soil-PA mixtures for %GC. Weeds were eliminated from the pots before estimating the final coverage (while others included them). Additionally, the preprocessed images were cropped along the pot inner diameter, meaning the coverage outside the pots was not accounted for. Therefore, the analysis shown in Figure 4.6-Figure 4.9 should be deemed as underestimates in comparison to the "true" vegetation coverage.

4.5.1.1 Effects of organic amendments on green coverage

The study employed four different soil types—Ortonville (O), Sanborn (S), Clearwater (C), and Glenwood (G)—and four organic amendments: Turkey Litter (TL), Biochar (B), Food-waste compost (F), and yard-waste compost (Y). An abbreviation system was used to describe the treatments, with the first letter representing the soil type, the second letter indicating the amendment, and the third letter corresponding to the application rate. The application rates are labeled as "A," "B," and "C." For instance, "OFA" refers to Ortonville soil with food-waste compost applied at rate "A," while "SBB" signifies Sanborn soil with Biochar applied at rate "B."

Ortonville: The greatest 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%), while the rest fell below the desired coverage of 70%, which is based on MnDOT NPDES (National Pollutant Discharge Elimination System) requirements (MnDOT 2017). Growth curves of the Ortonville-compost blends displayed a slow growth of the plants compared to the control soil "O", particularly in the first 9 weeks. TL compost did not produce any plant yield at higher application rates (B and C) even after 15 weeks of seeding. TL at rate A produced a few grass strands with time, covering only 17.4 ± 10.14% of the soil surface after 15 weeks of seeding. Alternatively, the biochar was the only OA (regardless of its application rates) that outcompeted the control in terms of %GC. Although biochar seemed to have improved coverage when mixed into soils, the %GC was not necessarily from the planted native species, but a predominance of weeds (Chenopodium album and/or Yellow Wood Sorrel) emergence. 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 from week 15 was reduced from week 13 in soil mixes (e.g., OTA, OTB etc.,) (Figure 4.7). Since this clayey soil already had an OM of 5.39%, addition of the OAs did not necessarily contribute to enhanced plant coverage. Ortonville is the only control soil that did not meet the 70% standard for coverage compared to the three sandy loam soils (S, C, and G).

Clearwater: 10 out of the 13 Clearwater soil mixes showed at least 70% coverage, with the highest coverage (93.4 ± 4.77%) recorded in the CFC blend. The control's coverage from the final week was 87.6 ± 5.91%, with only two other blends (CFC and CBC) exceeding this value. The growth curves demonstrate the B, FW and YW amendments superseded the control's %GC at least until week 11. Consistent with the observations of Ortonville-TL soils, the worst Clearwater soil mixes contained the turkey litter compost (TL) as well. Grass strands were again the only species collected from the CTA blends with 25.4 ± 16.8% GC, and 0% GC was seen in CTB and CTC soils by the end of the study. Clearwater soils had weeds (Cleavers) during the study period; however, since Cleavers did not densely cover the soils, unlike the prevalence of Chenopodium album in Ortonville, the %GC was not severely affected by the presence of weeds in the Clearwater blends.

Sanborn: Yard-waste amendment at rate B and rate 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 (77.1 ± 0.62%). The FW amended Sanborn soils supported plant growth only after week 5, but soon after climbed to 67.9 ± 11.82%, 80.3 ± 13.5% and 72.7 ± 2.32% for SFA, SFB and SFC, respectively, by week 15. Interestingly, although TL slowed seed germination and growth response (Figure 4.7), the %GC of the STA blend was 86.1 ± 6.9%, next in line to SYB and SYC at the end of the study. Additionally, the STB and STC growth was slower than STA; however, in one of the replicates of each of these soils, the black-eyed Susan surfaced along with other grass species. This improved the mean %GC and with STB and STC at 43.9 ± 44.3%, 42.3 ± 41.0% respectively, albeit with a high margin of variability. Only 3 out of the 39 Sanborn pots (including replicates) saw weeds (Yellow Wood Sorrel and Canada Thistle) which therefore did not contribute to the %GC estimates of these soils.

Glenwood: GTA is the only Glenwood soil that covered more (87.8 ± 2.41%) soil surface via vegetation than the control soil, G (79.6 ± 8.99%). Every other G-OA blend produced lower above-ground plant matter than G. TL, amended into Glenwood at rate A, did not suffer from any growth delays unlike STA, CTA, or OTA, and was successful in enhancing this soil for plant growth. GTB and GTC produced 65.1 ± 7.25% and 54.4 ± 28.6% GC, respectively, again greater compared to the corresponding TL rates of other soils. This trend was consistent across the board: the higher the application rate of TL, the lower the plant yield was. 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 (Figure 4.7).

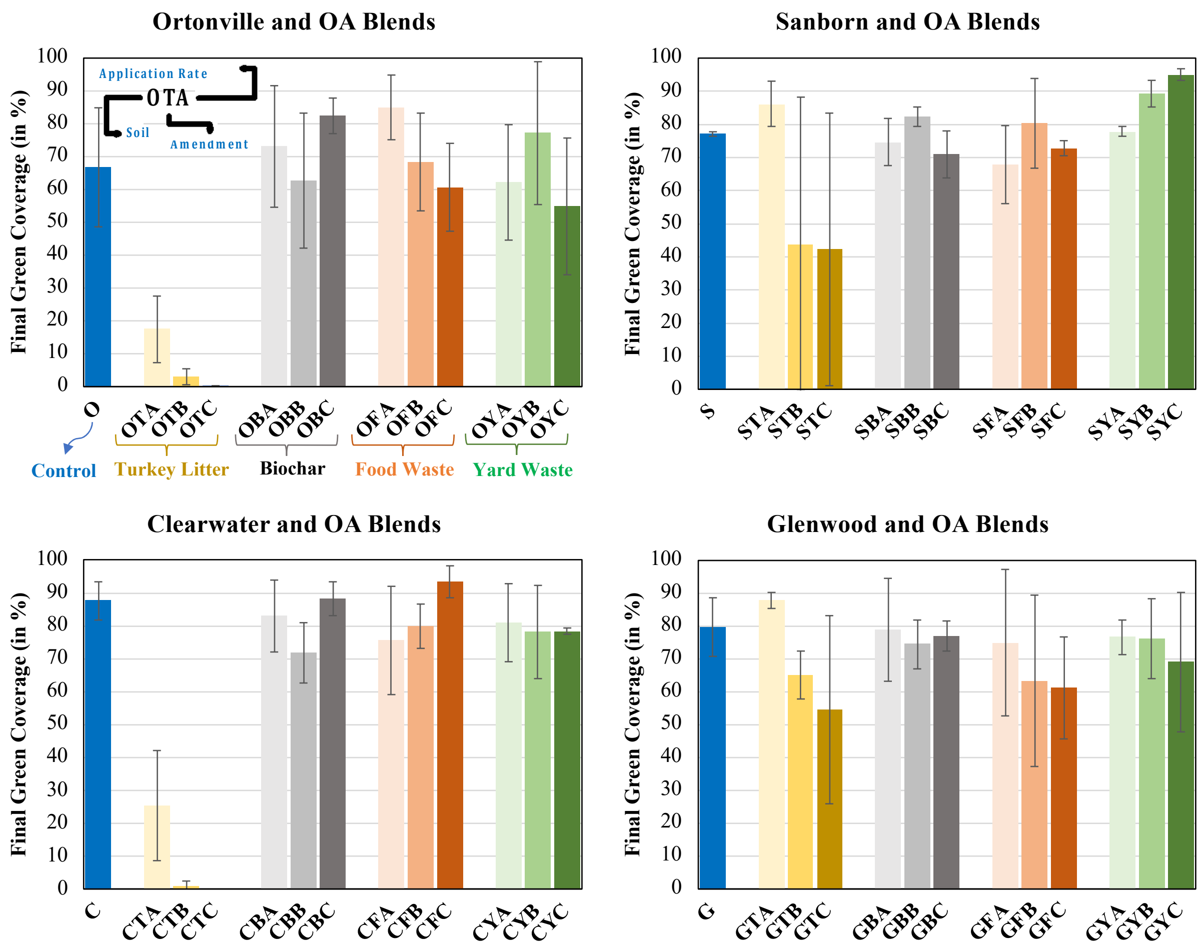


Figure 4.6 Final green coverage (%) of soil-OA blends in pot studies.

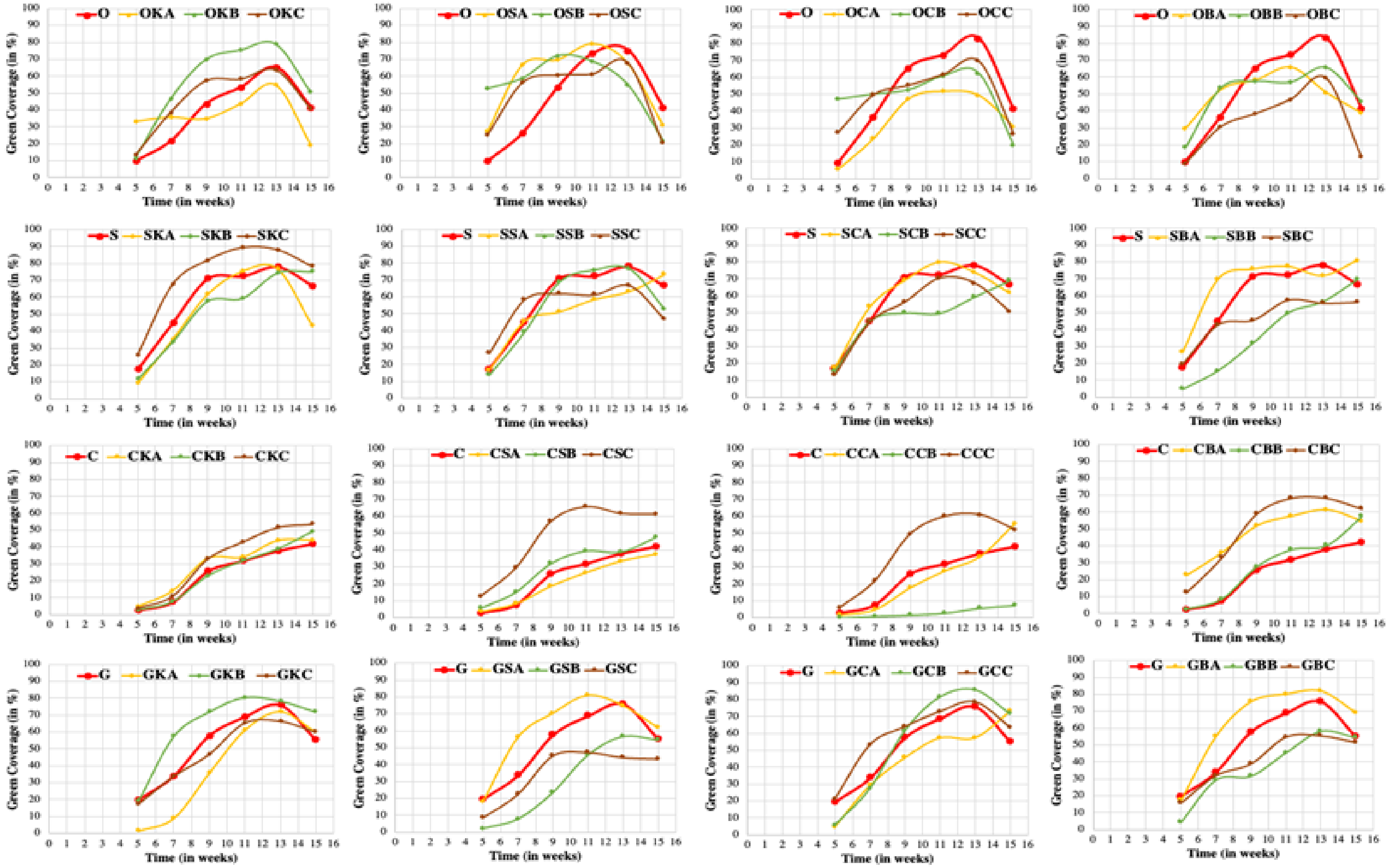


Figure 4.7 Temporal changes in %GC of soil-OA blends in pot studies.

Notes: Weeks 3 – 13 included weeds in the %GC analysis and week 15 did not.

4.5.1.2 Effects of proprietary amendments on green coverage

The study employed four different soil types—Ortonville (O), Sanborn (S), Clearwater (C), and Glenwood (G)—and four proprietary amendments: Sustane 4-6-4 (S), Carbogrow 3-0-3 (C), Kickstand Fe (K), and Biotic (B). An abbreviation system was used to describe the treatments, with the first letter representing the soil type, the second letter indicating the amendment, and the third letter corresponding to the application rate. The application rates are labeled as "A," "B," and "C." For instance, "OSA" refers to Ortonville soil with Sustane amendment applied at rate "A," while "SBB" signifies Sanborn soil with Biotic applied at rate "B."

Ortonville: Ortonville soil was observed to have inadequate vegetative coverage (Figure 4.8). This is because of the significant prevalence of weeds, and their removal at the end of the 15th week resulted in a noticeable reduction in coverage. Nevertheless, when the Kickstand mixtures were employed, an improvement of roughly 10% was noted compared to the control soil. For the Sustane blends, the elevated application rate led to a decrease in the extent of %GC. On the other hand, Biotic blends revealed an upward trend of between 2% and 5% at lower application rates.

At the low application rate, the Kickstand amendment initially produced a higher %GC, while in the subsequent weeks, the %GC of pots with higher application rates increased (approximately 30% higher). After 15 weeks, it was observed that the %GC of Ortonville reached 80 ± 0.19% at high application rates (rates B and C). From week 5 to week 7, all Sustane blends in Ortonville soil showed higher %GC than that of Ortonville soil alone (ranging from 25 ± 0.13% to 55 ± 0.08%). After the 7th week, growth acceleration started to decrease and the control soil hit 53±0.10% GC; Sustane blends showed slight changes. The low application rate for Sustane blends, on the other hand, exhibited growth of up to approximately 80 ± 0.07%. Although the high application rate of Carbogrow blends had a higher %GC than that of Ortonville soil until the 8th week, the %GC of Ortonville soil alone surpassed the %GC of Carbogrow in the 15th week. Biotic soil amendment did not appear to improve the %GC of Ortonville soils as it was observed that this amendment resulted in lower %G, C especially in the long term from week 8 to week 15 (Figure 4.9).

Sanborn: Sanborn soil appeared to be the most productive and fertile soil in terms of vegetative coverage (%GC). Although the %GC of Sandborn alone was high (67 ± 0.08%) in the final week, the PAs still seemed to improve their %GC performance (Figure 4.8). In the case of Biotic and Kickstand amendments, %GC increased by almost 20%, especially at application rates A and B. On the other hand, it was observed that Sustane improved the %GC up to 15% at lower rates (Rate A) while lower %GC performance was noticed at manufacturer recommended and higher application rates (Rates B and C). Carbogrow displays a fluctuating trend in terms of %GC. While no trend was found between application rates of Carbogrow and %GC, it was observed that this amendment yielded slightly higher %GC than that of Sanborn control soil.

The %GC in Sanborn blends increased significantly until week 9 for almost all conditions, while plant growth acceleration decreased thereafter. The Kickstand amendment consistently provided higher %GC with manufacturer recommended and high application rates (Rates B and C), resulting in plant growth increasing up to a maximum of 90 ± 0.04 %, which was higher than the growth seen in Sanborn soil alone. Sustane's high application rate (Rate C) up to the 9th week appeared promising, but the rate of %GC declined in the following weeks. %GC was 80 ± 0.08% for both Kickstand and Sustane at high application rates (B and C) and 63 ± 0.3% for low application rates (A). Carbogrow showed positive results for time-dependent development at low application rates (Rate A) until the 11th week, with plant growth starting to decrease between the 11th and 15th week (end of the study). Biotic blends demonstrated a similar trend as Carbogrow in terms of growth continuity until week 11, with higher %GC values observed at low application rates (Rate A). However, Sanborn-Biotic blends at application rates A and B always had higher %GC than that of Sanborn soil alone throughout 15 weeks (Figure 4.9).

Clearwater: The addition of proprietary amendments to the Clearwater soil resulted in improvement in %GC (Figure 4.8). Kickstand, Sustane, Carbogrow, and Biotic blends demonstrated 10%, 20%, 12%, and 20% higher GC than Clearwater soil alone, respectively. Even at low application rates, the results were similar to the Clearwater soil in general.

Clearwater resulted in lower %GC values (68%) compared to other soils (Sanborn, Glenwood and Ortonville). Kickstand at high application rates (Rate C) steadily increased the %GC of Clearwater and reached 70%. Due to low weed presence, the high application rates of Kickstand improved %GC of Clearwater soil. Sustane at manufacturer recommended and high application rates (B and C) increased %GC of Clearwater by 2 times. Similarly, high application rates of Carbogrow led to an increase in %GC of the soil (~90%). Furthermore, all application rates of Biotic increased the %GC of Clearwater (with an increase as high as 2.5 times).

Glenwood: Low rate applications of all amendments appear to improve the %GC of Glenwood soil while Kickstand and Carbogrow blends at rate B also yielded higher %GC than that of Glenwood soil alone (Figure 4.8). Results showed that the best performance for Glenwood soil was obtained from Kickstand PA which yielded the highest mean %GC (%72± 0.17) for this soil at application rate B at the final week (Week 15).

Application B of Kickstand showed a higher %GC than all the other Glenwood blends. The low application rate (A) of Biotic blends also outperformed the %GC of Glenwood soil alone. However, only the lowest application rate A for the Sustane blends provided higher %GC for Glenwood soil. Starting from Week 9, the manufacturer recommended application rate B of Carbogrow started to outperform the %GC of Glenwood soil alone. The application of Biotic at low application rate A resulted in higher coverage than that of the control and other Carbogrow-Glenwood blends. Moreover, low application rate A of Biotic provided the highest %GC within the Biotic blends for Glenwood soil.

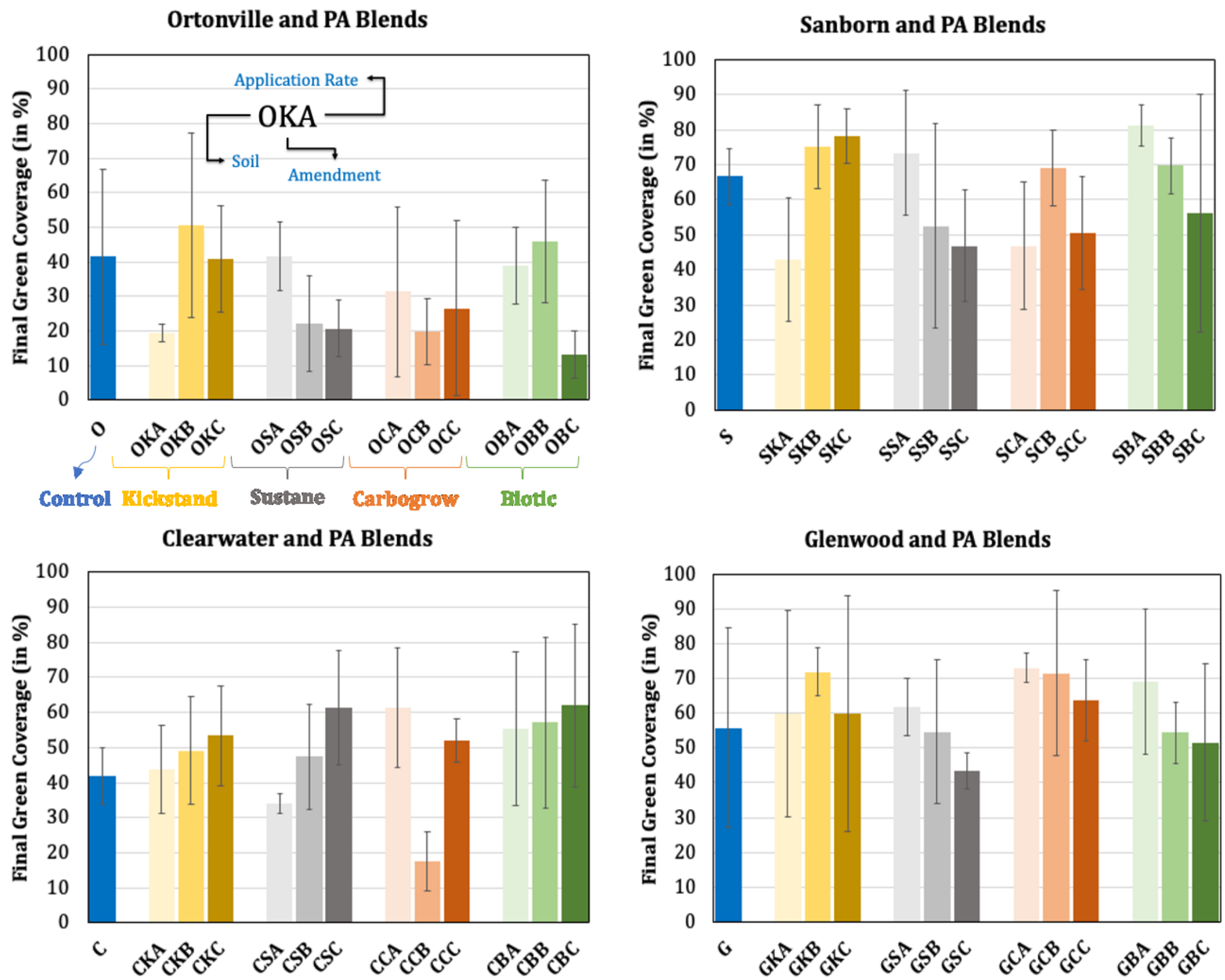


Figure 4.8 Final green coverage (in %) of soil-PA blends in pot studies.

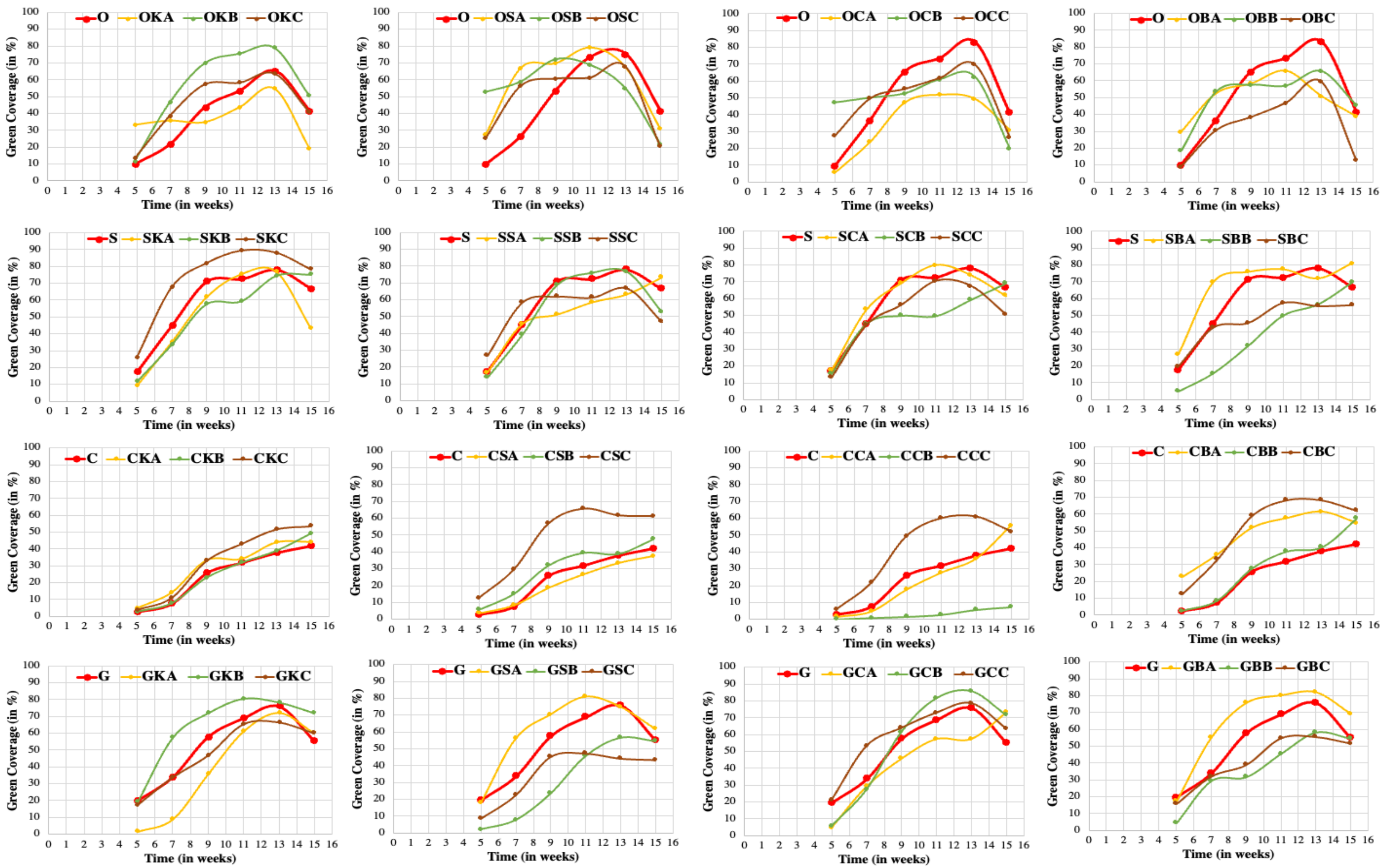


Figure 4.9 Temporal changes in %GC of soil-PA blends in pot studies.

Notes: Weeks 3-13 included weeds in the %GC analysus and week 15 did not.

4.5.1.3 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 caused by the turkey litter and green waste-based compost (TL) amendments. To investigate the dependence of plant response to soluble salts, the EC of all the 52 soil blends was measured at the initiation of the experiment and plotted against the dependent variable (%GC) for every two-week period (week 3 until week 15, Figure 4.10). 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) increasing over time along with high ($p < 0.00001$) statistical significance. This switch from exponential to linear correlation between %GC and salts occurred because, with each watering event, the salts become translocated deeper from the root zone, making the topsoil layer more favorable for seed germination and growth. Figure 4.11 gives visual evidence to the best compared to the worst performing soil-OA blends. Clearwater soil amended with TL at rate C did not produce any vegetation yield because of a soluble salts level (EC) of 5137 ± 37.9 μS/cm, even after 15 weeks of seeding, while YW displayed full coverage when amended into the Sanborn soil at rate C (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).

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). TL 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 4.3). 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). 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. Greater salts and ammonium contents in TL appear to have curtailed the growth and development of the plants.

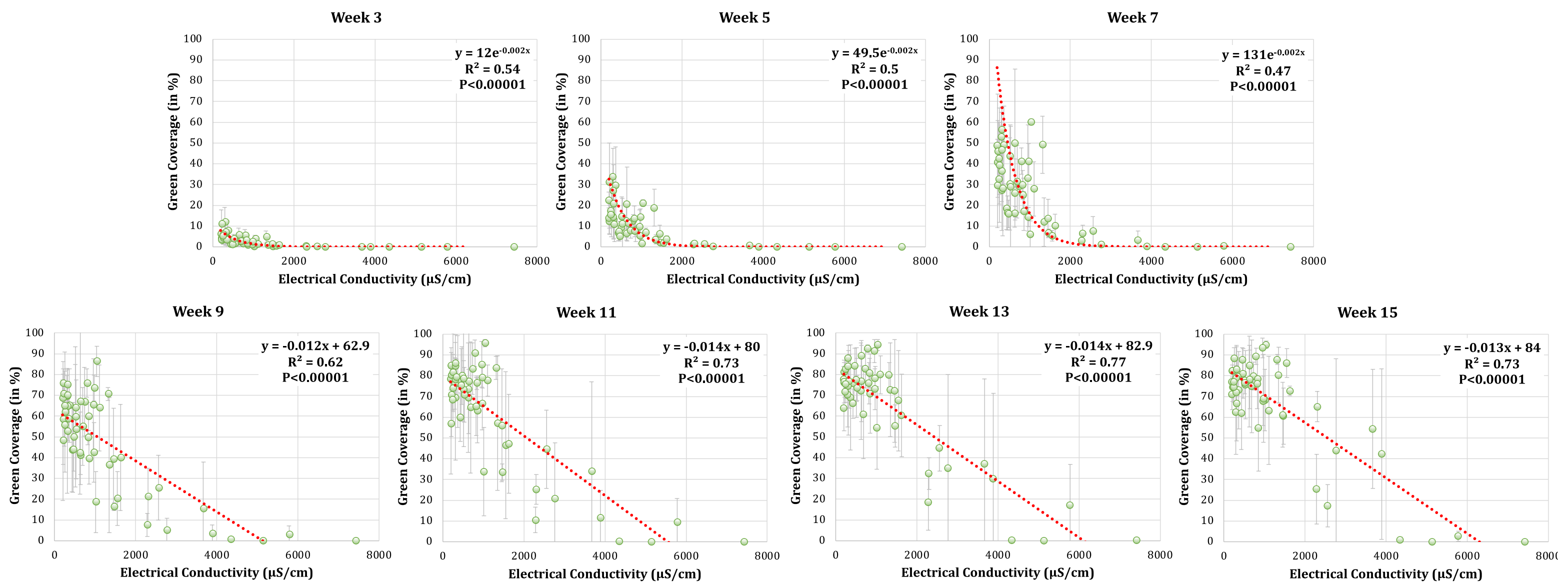


Figure 4.10 Correlation plots of green coverage vs soil soluble salts (EC) for the pot study.

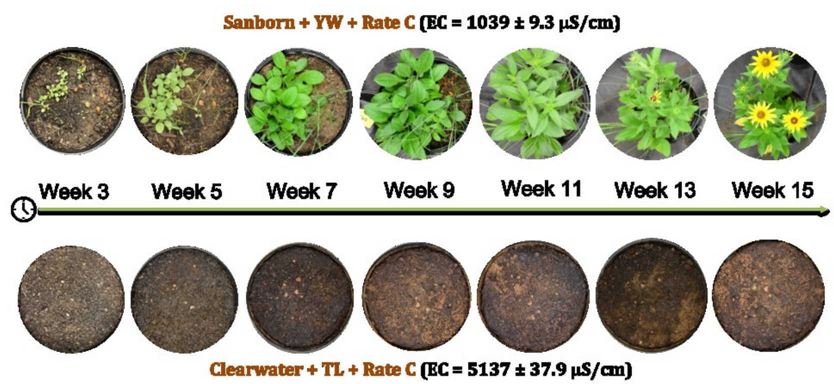


Figure 4.11 Comparison between best vs worst performing soil-OA blend for the pot study.

4.5.2 Plant Biomass and Growth Index

4.5.2.1 Effects of organic amendments on biomass and GI

Ortonville: TL compost was the only OA in Ortonvillle soil that did not produce plant dry matter (Figure 4.12). As discussed above, excess salt and ammonium content contributed to suppressed growth in these blends. Biomass production from the other amendments and application rates showed reduced growth compared to the control, O, except for OFA. As previously mentioned, Ortonville soil had weed emergence, and this was especially dominant in the blends with biochar, which is why the soil-biochar blends recorded higher %GC compared to soil O. Weed presence was not reflected in the above-ground biomass, because the measurements did not include weeds. Growth Index (GI) of BES plants from the Ortonville soil mixes provided similar findings to biomass; the GI of the plant did not improve when OAs were added to this soil (Figure 4.13). Since Ortonville contained acceptable levels of OM (5.39%), it provides greater plant available nutrients than other soils. Thus, the influence of OAs on biomass and GI were not clearly observed.

Clearwater: Like Ortonville and as noticed previously in the GC results, the Clearwater soil demonstrated an inability to grow vegetation when amended with the TL compost, owing to soluble salts (Figure 4.12). FW at rate B and C (CFB and CFC) yielded 42.3% and 80.1% more plant biomass compared to the reference soil. This increase was followed by CBA (26.9%) and CYB (16.3%), with other amendments showing an increase of less than 10%, or reduced growth altogether. The most 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 in GI of 17.5% and 22.1% respectively. Overall, Clearwater benefited the most from the FW amendment compared to other OAs.

Sanborn: YW 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. TL at rate A also enhanced above-ground productivity, while rates B and C stunted growth, tying the discussion back to the salts contents of these mixes. However, TL compost rates B and C produced some biomass (~4.4 ± 5.6 and 4.3 ± 5.4 g, respectively) by the end of the study. The large margin of error results due to growth variability in the pots. Sanborn-TL blends contained lower salts content compared to the corresponding Ortonville- and Clearwater-TL blends and correspondingly provided a more conducive environment for plant growth. Although the biomass production was the greatest in SYB and SYC, the GI of BES plants in these pots did not statistically improve ($p > 0.05$) compared to the control soil (S) (Figure 4.13). On the other hand, the biomass production from Sanborn-TL mixes was lower at higher rates of application B and C. However, GI was positively influenced (STA, 52.1%; STB, 42.1%; STC, 35.4% increase compared to S) by the addition of TL. This suggests a morphological benefit to plants when mixed with high N (2.69%, Table 4) amendment as long as salts content is not excessive.

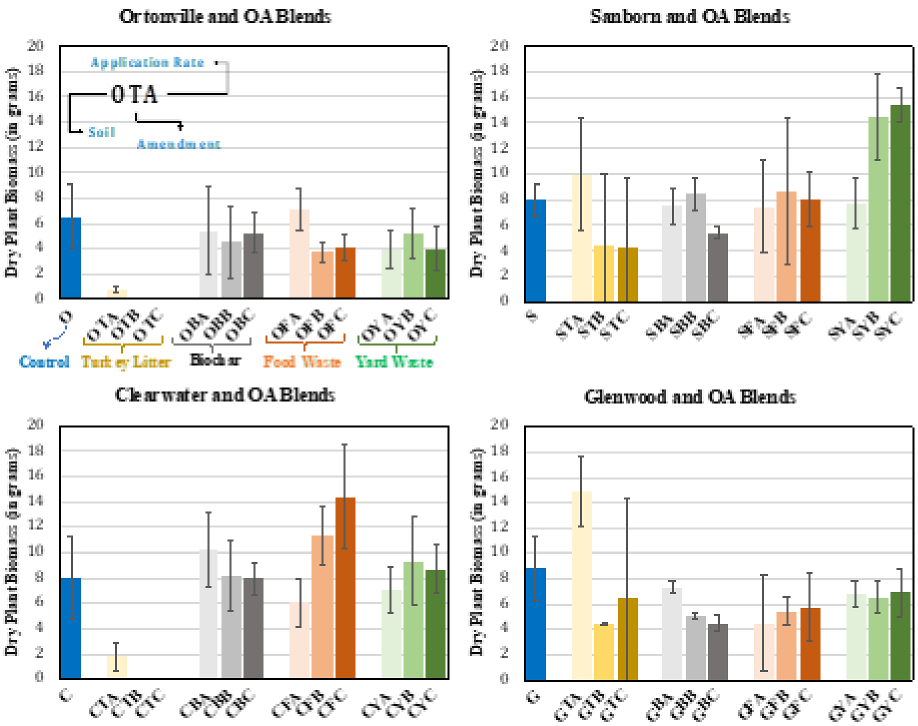


Figure 4.12 Dry plant biomass (in grams) in soil-OA blends from pot studies.

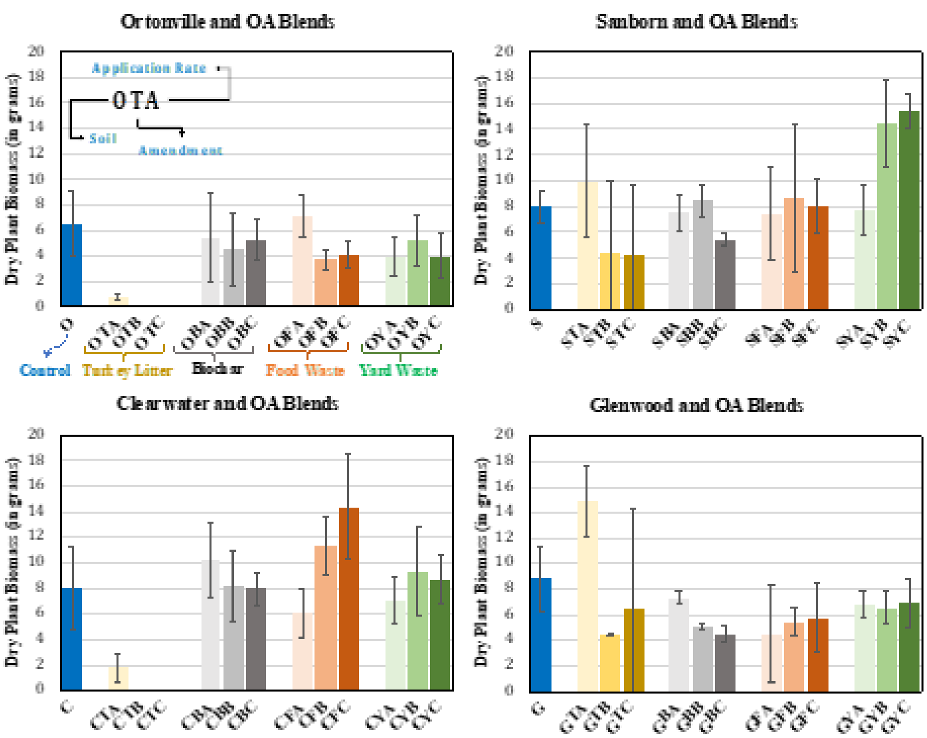


Figure 4.13 Growth Index (in inches) of black-eyed Susan from soil-OA blends from pot studies.

Glenwood: Except for GTA (which increased BES GI by 18%), every other soil blend showed a negative influence on biomass for the Glenwood soil (Figure 4.12). The biochar OA decreased the biomass 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 injure plant growth by retaining the N in the soil and reducing the plant available fraction (USDA NRCS 2011). Biochar fits this scenario, meaning amending soils with biochar increases the C:N ratio of the Glenwood-B blends, as high as 117:1, whereas the ratio for unamended Glenwood was 10.2:1 (Table 4). Unexpectedly, FW and YW also developed biomass that was 34.9 to 49% (FW) and 21.9 to 26.2% (YW) less compared to reference soil. 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. This could have adversely affected growth because of increased OA application.

4.5.2.2 Effects of proprietary amendments on biomass and GI

Ortonville: It was observed that PAs did not result in higher biomass growth for Ortonville soil. Kickstand at rate B yielded similar biomass as the Ortonville soil alone. Based on these results, it appears that additional/excessive mixing ratios of PAs are not contributing in terms of biomass growth. The biomass of Ortonville is relatively small compared to other soils having high BES yields. This is because spindly grasses were prone to growing at higher rates than plants with large biomasses. Ortonville soil had the highest weed dominance and after removal of weeds, a decrease in growth index was observed in all Ortonville mixtures except for the Carbogrow (rate C) blend.

Clearwater: Clearwater blends also did not increase biomass accumulation, particularly with Kickstand amendments at any applications rates; low rates of Biotic and Carbogrow (CBA and CCA) and a high rate of Sustane (CSC) amendment resulted in increase in plant biomass of Clearwater alone by 20%. The highest improvement was achieved at the lowest application rate (A) of Biotic PA (despite the high margin of error).

BES did not thrive in Clearwater in many cases. Control pots alone accumulated greater GI than that of blends and the growth index did not increase. However, depending on the application rate, the growth index increase is considerable in the Clearwater-Sustane (CSB-CSC) and Clearwater-Biotic (CBA-CBB) (40% and 30%, respectively)

Sanborn: Sanborn soil was the most effective in achieving higher biomass accumulations. The increase in PA application rates caused a decrease in biomass by almost half in Carbogrow and Biotic blends. More specifically, at lower application rate A, all PAs seem to increase the biomass accumulation (~1.5 times), while application rates B and C for Carbogrow and Biotic amendments hindered the biomass accumulation. On the other hand, Sanborn-Sustane blends did not provide any trend between application rates, but the overall trend showed that they increased the biomass accumulation at the range of 20% to 50%. Kickstand PA was less effective in increasing biomass accumulation of Sanborn soil and yielded a slight improvement.

All PAs increased the GI vegetation grown in the Sanborn soil. At low application rates (A), this increase was in the range of 10%-80% while it was almost 100% at higher application rates B and C. Kickstand, Sustane, and Carbogrow exhibited growth improvement with an increase in application rate from rates A to C. Conversely, biotic amendment led to reduced plant growth at higher application rates but still resulted in overall increased growth compared to the Sanborn soil alone.

Glenwood: Sustane, Kickstand, and Biotic PAs did not improve the biomass accumulation of Glenwood soil when applied at any application rates, while Carbogrow blend showed a significant increase (~1.5 to 2) times when applied at a low rate (A) and high rate (C), respectively.

In terms of GI, the Kickstand amendment was less effective when used in lower quantities (rate A) but performed better at higher application rates (rates B and C). On the other hand, Sustane yielded satisfactory results by promoting plant growth by 25% to 50% as the application rate increased. The growth rates were similar to the control at lower application rates in Carbogrow blends and showed an increasing trend as the application rate increased. With the Biotic amendment, all application rates produced similar results, suggesting that application rates may not have a significant effect on plant growth for Glenwood soil.

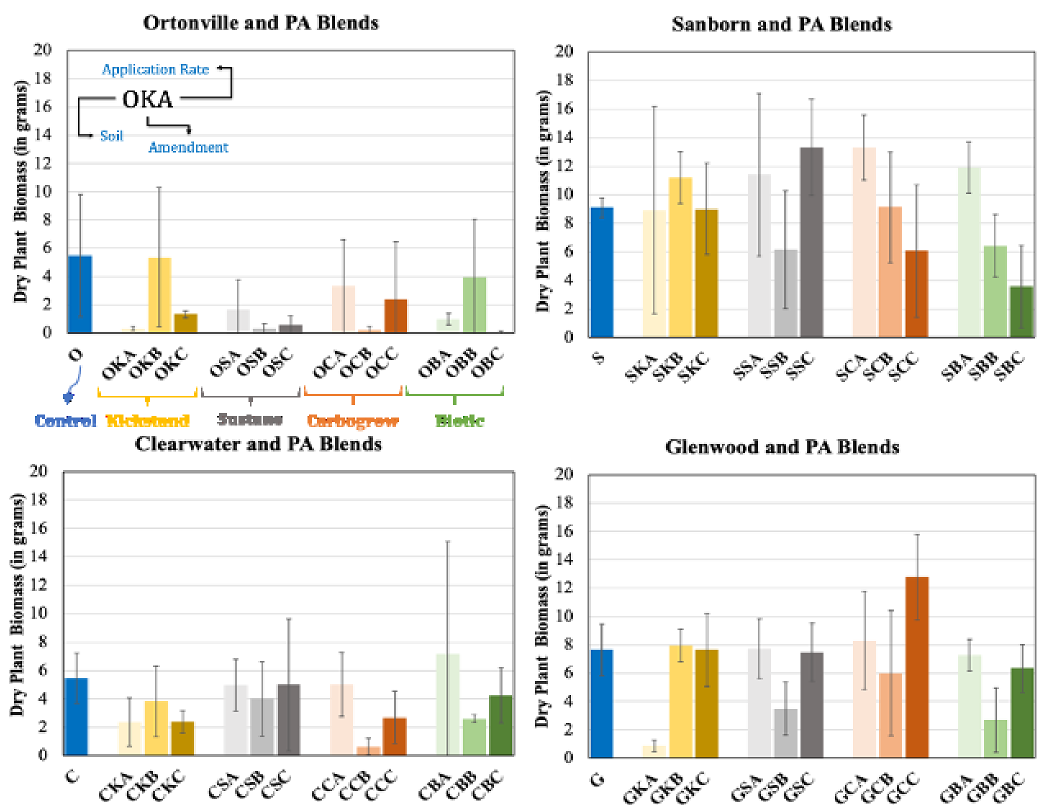


Figure 4.14 Dry Plant biomass (in grams) in soil-PA blends from pot studies.

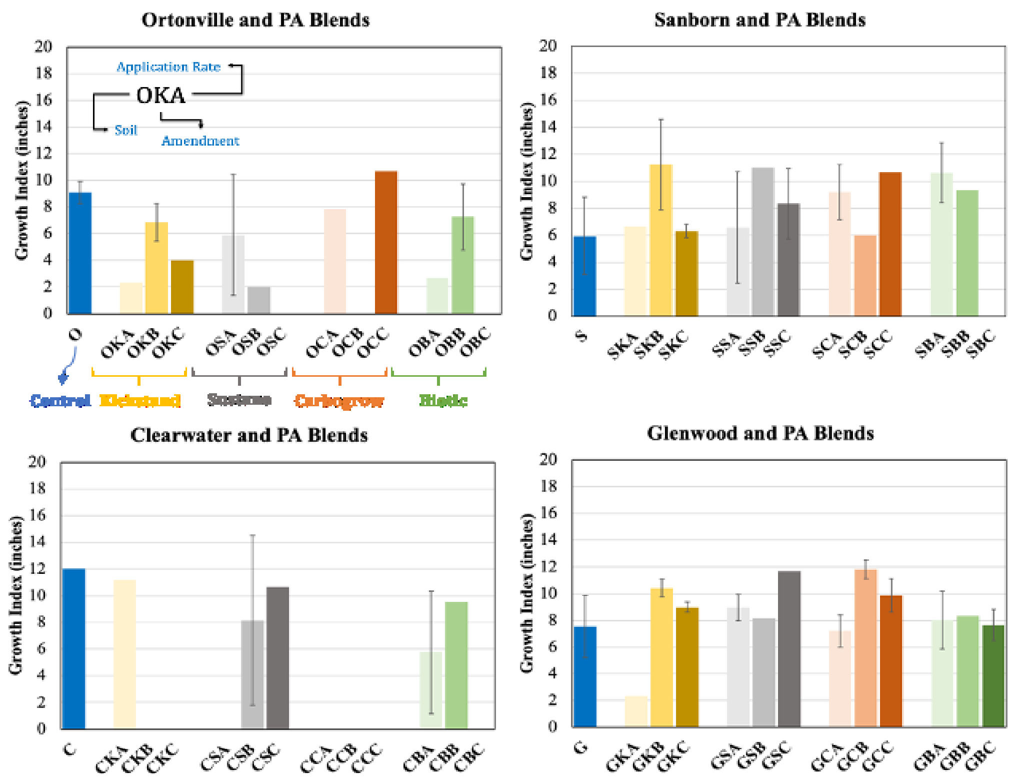


Figure 4.15 Growth index (in inches) of black-eyed Susans from soil-PA blends from pot studies.

4.5.3 Plant Nitrogen and Leaf Area

Figure 4.16 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 TL = 2.67 ± 0.09%, FW = 1.7 ± 0.07%, Y = 1.39 ± 0.08% and B = 0.67 ± 0.03% (Table 4). Across the board of soils, biochar amendment showed reduced N (also visually less green, Figure 4.5) in the BES leaves compared to OA soil mixes and controls (except Sanborn). Sanborn soil contained 0.18% N and the lowest plant available NO_3-N (6.1 ± 0.11 mg-N/kg) and OAs; this lack of plant nutrient manifested in the BES leaves of the control soil (S), noting the lowest N uptake (2.3%). Of the composts, for at least one rate of application, the BES %N in YW-soil was less than ($p<0.05$) the corresponding value for FW- and TL-soil of any soil. Typically, less than 3% N in plants can induce deficiencies and affect the quality (Plank 1992). Although biochar produced greater plant coverage in the early 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). Alternatively, the higher NH_4 content from the TL compost prompted greater N uptake in the BES plants and grasses of Glenwood- and Sanborn-TL amended soils. Saloner and Bernstein (2022) also reported higher N accumulation in the cannabis plant with increased NH_4 and NO_3 supply.

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 along with N%. Figure 4.17 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 (Figure 4.5). Only two soils (Sanborn and Glenwood), when amended with TL grew BES, and the leaves of these plants looked greener and larger compared to other soils.

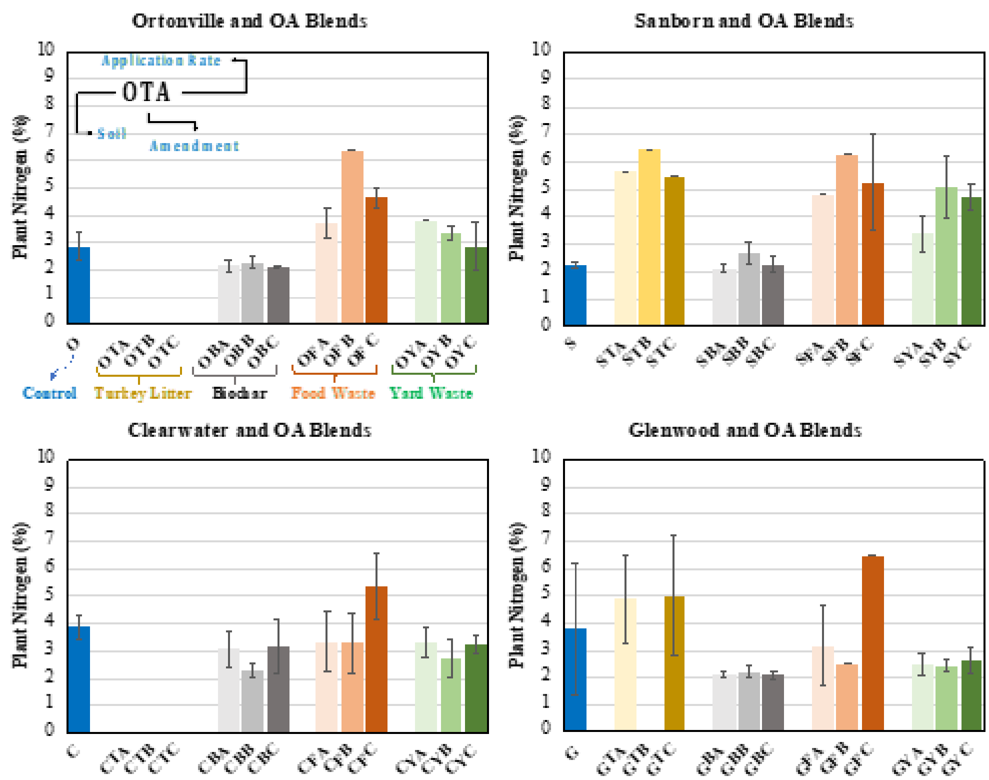


Figure 4.16 Plant nitrogen (%) of black-eyed Susan from soil-OA blends from pot studies.

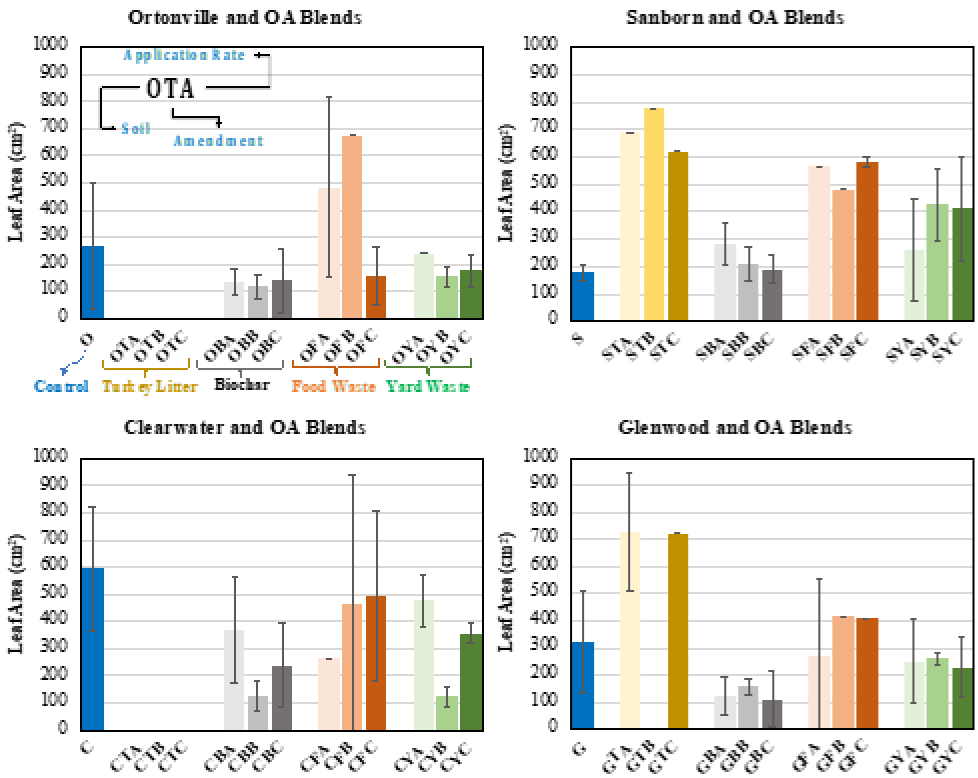


Figure 4.17 Leaf area (cm²) of black-eyed Susan from soil-OA blends from pot studies.

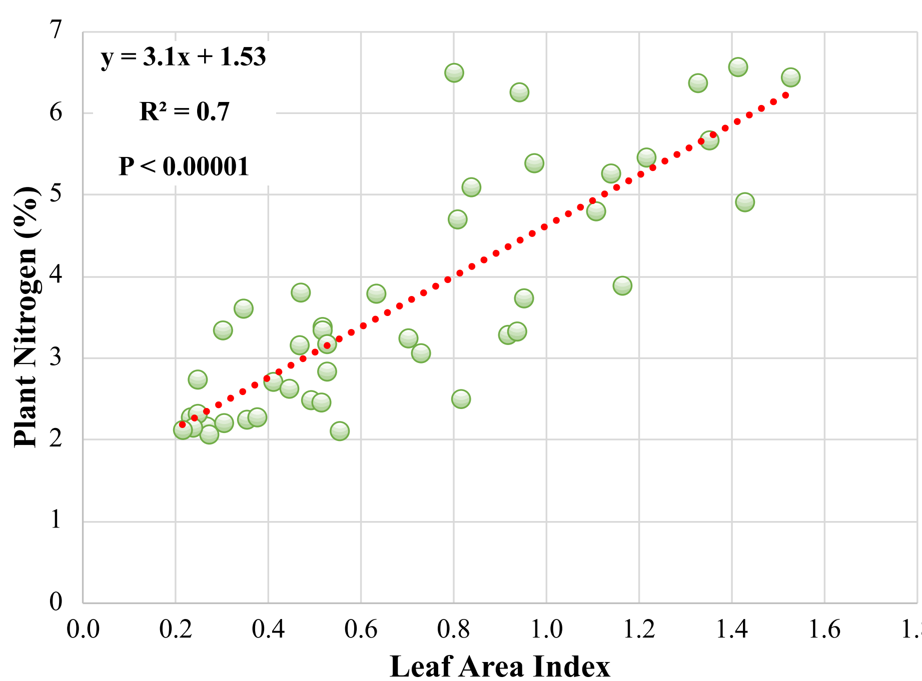


Figure 4.18 Correlation between plant nitrogen and LAI of black-eyed Susan plants from pot studies.

The plant uptake of nitrogen is plotted against the leaf area index (LAI) to emphasize the correlation between the two parameters (Figure 4.18). LAI is an 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 leaf area of the healthiest BES plant per pot and dividing it by the pot diameter (507 cm^2 or 78.54 $inch^2$), which represents the ground 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. Figure 4.18 demonstrates that plant N is linearly related ($p < 0.00001$) to the plant LAI (Figure 4.18). 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 plant available N content.

4.6 Chapter Conclusions

4.6.1 Organic Amendments

Three composts (YW, FW and TL) and one wood-based biochar (B) were evaluated for rapid vegetation growth on four topsoils. 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 TL amendment either delayed or stunted plant growth in the soils.
2. Correlations between GC and EC showed that soils with EC greater than 2000 μS/cm can be a deterrent to plant production.
3. High NH_4 content and NH_4:NO_3 ratio of the TL amendment may induce ammonium toxicity and impair plant health.
4. 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.
5. Visually, plants growing in the soil-biochar media experienced nutrient deficiencies (yellowing of leaves, crusty edges). 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.
6. In Sanborn and Glenwood soils, N uptake was higher in the BES plants emerging from TL compost followed by FW and then YW. Also, a similar trend was followed for the LAI of BES in these soils.
7. Greater biomass was accumulated from the Sanborn-YW blends and Clearwater-FW blends at rates B and C. Between YW and FW, the latter contributed to higher uptake of N and leaf area compared to YW.

4.6.2 Proprietary Amendments

Four different proprietary amendments (PA) (Kickstand, Sustane, Biotic, and Carbogrow) were evaluated for rapid vegetation growth on the four topsoils. Similar to the OA, the findings below can guide the selection of PA use.

1. The %GC of Ortonville soil increased with an increase in the application rate of Biotic PA. Kickstand and Biotic at Rate B improved the %GC of Ortonville soil, whereas Sustane and Carbogrow did not seem to have an impact on the %GC.
2. Sustane and Biotic at Rate A produced a higher %GC than that of Sanborn soil alone. An increase in the application rate of Kickstand and Carbogrow yielded an increase in the %GC of Sanborn soil.
3. Lower rate application (Rate A) seemed to enhance the %GC in Glenwood soil. Nearly all PAs achieved a higher %GC than that of Glenwood soil alone.
4. PA addition to Clearwater soil led to up to 50% increase in %GC. The %GC increased with an increase in PA content regardless of PA type, except Carbogrow.
5. PA additions did not show dramatic biomass accumulation for Ortonville soil, whereas Sanborn demonstrated higher biomass. Addition of Biotic and Carbogrow increased the biomass 40% to 50% at lower application rates. Kickstand and Sustane also exhibited a 30% to 50% increase in biomass.
6. Except for Carbogrow applications in Glenwood soil, Kickstand, Biotic, and Sustane did not enhance biomass growth. For Clearwater soil, Biotic increased biomass at Rate A.
7. GI tended to decrease, except for the high application rate (Rate C), of Carbogrow in Ortonville soil (OCC). Clearwater soil alone exhibited a significant GI (12 inches); however, an increasing trend in GI was found in Clearwater-Sustane (CSB-CSC) and Clearwater-Biotic blends (CBA-CBB), depending on the application rate.
8. The GI showed a twofold increase in response to Rate B and Rate C of Kickstand, Sustane, and Carbogrow, while Biotic at Rate A resulted in a 1.5-fold improvement in Sanborn soil.

Chapter 5: Greenhouse Mesocosm Study

Roadside vegetation is a cornerstone for combating soil erosion, improving stormwater quality, and providing effective landscape management. In horticulture and agricultural practices, crop yield is often enhanced using inorganic or organic fertilizers. In a parallel approach, the state departments of transportation (DOTs) have been motivated by the necessity for rapid growth of roadside vegetation. To achieve this, the DOTs have been evaluating organic amendments (OA) such as compost and biochar, and inorganic or proprietary amendments (PA) similar to NPK fertilizers, to facilitate rapid vegetation growth.

Organic amendments (OAs) are inexpensive, widely available, and provide great nutritional and structural benefits to urban soils. 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 (Kranz et al. 2020). Additionally, depending on their constituent source elements, OAs have the potential to treat stormwater contaminants. While the application of OAs seems positive from vegetation and hydraulic aspects, previous research has raised concerns about the use of such nutrient-dense organic materials (composts) due to excessive nutrient leaching, which may worsen the existing problem of stormwater nutrient pollution (Puppala et al. 2011, Owen et al. 2021). This loss of nutrients to surface water can impair downstream waterbodies and worsen eutrophication-related issues. Another carbon-rich organic material that is of interest is biochar. Biochar is produced by thermal combustion of biomass in an oxygen-deficit environment (pyrolysis). The structure and stability of the biochar product depend on its feedstock sources (e.g., animal manure, wood waste), pyrolysis temperature, and heating rate. Biochar addition has proven to be an effective soil remediation strategy, improves soil porosity, adsorbs contaminants, and enhances stormwater quality. On the other hand, some biochar amendments, particularly those made from wood waste, can lack plant-available nutrients (N and P) and may limit vegetation (Agegnehu et al. 2017; Singh et al. 2010). This was also noted in the preceding experiment of the project.

The singular contribution 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 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 orthophosphate and nitrate leaching. In their literature review, Agegnehu et al. (2017) found the popularly used biochar in research was derived from woody materials, and there was a paucity of research in understanding biochar-compost integrated soil systems in large field-scale experiments.

One of the goals of this study 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. This study is one of the first efforts to evaluate 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 and wood-derived biochar in terms of vegetative health, this study hypothesizes that a mixture of compost and biochar incorporated into soils can improve soil fertility, plant uptake of nutrients, and soil hydraulic properties, 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.

Furthermore, the use of proprietary amendments influences vegetation growth, and biomass accumulation. Proprietary amendments, often containing a mixture of organic and/or inorganic compounds designed to address specific soil and nutrient deficiencies, are important in promoting nutrient availability and favorable soil conditions. Nitrogen (N), phosphorus (P), and potassium (K) are nutrients that are considered essential for plant growth, health, and susceptibility to deficiencies. In terms of micronutrients, iron (Fe) is part of photosynthesis and N_2 fixation and respiration processes (Havlin et al. 2016). Linde and Hepner (2005) addressed the positive effect of proprietary amendments with different NPK ratios on turfgrass establishment. Brown and Gorres (2011) showed synthetic slow-release and natural-based fertilizers effectively speed up vegetation establishment in Rhode Island, albeit in different soil conditions. Ettebb et al. (2020) investigated perennial grasses with different NPK treatments for vegetation coverage performance to reduce soil erosion for slopes. The treatment with NPK combinations was observed to enhance nutrient uptake and soil fertility in Sudan grass and Rye grass (Li et al. 2010). While the soil and plant health benefits of inorganic fertilizers increase water-holding capacity, soil aggregation, and plant/root growth, there is the possibility of environmental contamination by the leaching of nutrients. Therefore, management is crucial for N fertilizers that have the potential to contaminate groundwater and soil (De Pascale et al. 2006). As a coarse textured soil is highly susceptible to N losses, soil amendments that increase soil cation exchange capacity (CEC) and water holding capacity help minimize nitrate and ammonium leaching (Barton and Colmer, 2006).

Considering the importance of essential macronutrients and micronutrients for plants, one of the objectives of the mesocosm study is to conduct a comprehensive assessment of the performance of proprietary amendments-soil mixtures in terms of vegetation growth, water quality, and soil physiochemical characteristics. This work investigates the impact of a micronutrient-iron-based amendment (Kickstand) and NPK-rich amendments (Sustane 4-6-4) and NK-rich amendment (Carbogrow 3-0-3). These amendments have exhibited promising results in the pot experiment (Chapter 4). Collectively, the results of this study help delineate practicable recommendations by promoting the safe and beneficial use of OAs and PAs on roadside projects.

5.1 Experimental and Analytical Methods

Soil: Sanborn soil was chosen as the test soil in the mesocosm experiments, as both the organic amendments (OAs) and proprietary amendments (PA) improved overall plant growth in this soil. The Sanborn soil's organic matter content was determined to be 4.2±0.14%. Since the soil falls within the accepted range of 3-15% OM related to MnDOT topsoil specifications, it was therefore decided to dilute the soil's OM by mixing it with inorganic sand. This resulting control soil (C) contained 67% Sanborn, 12% medium (0.8-0.3 mm) inorganic sand, and 21% fine (0.6-0.2 mm) inorganic sand. These proportions were determined to ensure that the particle size distribution of the original Sanborn soil was not significantly altered (Figure 5.1). The OM content of the C soil was then measured to be 2.62±0.05%. The plastic limit (PL), liquid limit (LL), specific gravity (G_s), and particle size distributions of Sanborn and Control soils were determined by following ASTM D6913, ASTM 4318 and ASTM D7928 standards. Table 5.1 shows the physical properties and classification of soils in accordance with the Unified Soil Classification System (USCS) and the United States Department of Agriculture (USDA). Figure 5.1 depicts the particle size distribution curves of the two soils.

Table 5-1 Physical properties and classification of soils

Soil	%Gravel	%Sand	%FC	LL (%)	PI (%)	USCS	USDA
Sanborn	6	66	29	24.4	NA	SC-SM	Sandy Loam
Control	5	75	20	NA	NA	SM	Sandy Loam

Notes: SC-SM: Silty clayey sand, SM: Silty sand, LL: Liquid limit (ASTM D 4318), PI: Plasticity index, FC: Fine content (ASTM D6913 and ASTM D 7928)

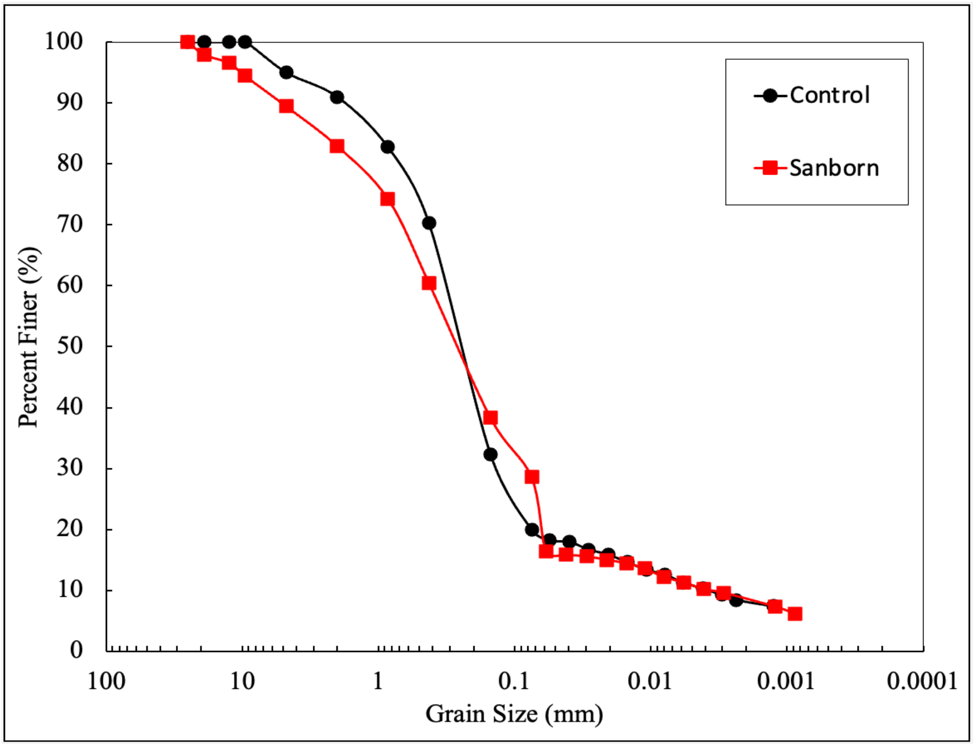


Figure 5.1 Particle size distribution curves of soils.

Organic Amendments: One compost produced from *yard waste* (Y), and one *wood-derived* biochar (B) were the two OAs chosen for this study at UMD. The former was obtained from *The Mulch Store* and the latter was shipped from the *American Biochar* company. The OAs were incorporated (independently and together) into C to increase the soil OM content by 4%. 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) (Table 5.2).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 (Figure 5.2). All 6 soil properties were analyzed at UMD Environmental Engineering Laboratories for pH, EC, OM%, C and N to assess soil fertility. Information pertaining to soil chemical analysis is presented in Table 4.1, and the soil and individual OA properties are given in Table 4.3 and Table 5.3.

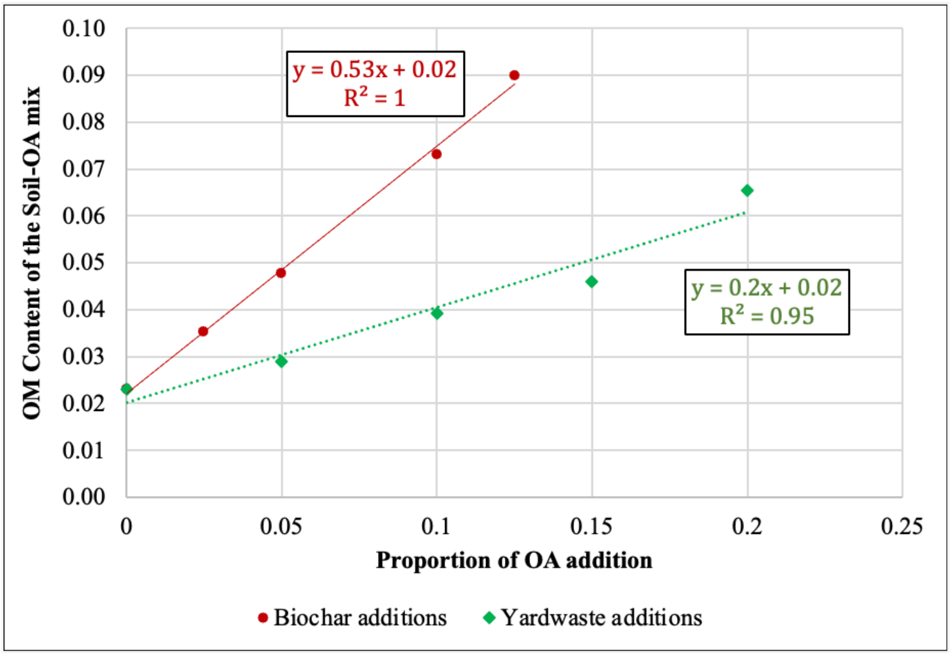


Figure 5.2 Regression equations used to estimate the amounts of OAs, Sanborn soil, and sands to achieve the target OM content (6%) of the soil-OA blends.

Table 5-2 Six OA-based soil media and their properties

Media	ID	Dry Bulk density in the box (g/cc)
Sanborn	S	1.47
Control	C	1.47
Control + Yard-waste Compost	CY	1.18
Control + Biochar	CB	1.28
Control + 50% Yard-waste Compost + 50% Biochar	CYB	1.2
Control + 75% Yard-waste Compost + 25% Biochar	C3YB	1.27

Table 5-3 Chemical characterization of OA-soils

Property	Sanborn (S)	Control (C)	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 (mS/cm)	292±3.58	208±2.38	789±97.46	227±6.87	457±7.44	628±14.6
OM (%)	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:N*	14.3±0.2	15.5±1.1	13.4±0.54	55.3±1.13	23.4±0.28	17.5±0.33
C (%)	2.53±0.02	1.45±0.04	3.84±0.24	6.5±0.05	5.15±0.15	4.46±0.22
N (%)	0.18±0.004	0.09±0.004	0.29±0.03	0.12±0.003	0.22±0.004	0.26±0.008

Proprietary Amendments: Three PAs, iron-based amendment Kickstand+Fe, Carbogrow 3-0-3 and Sustane 4-6-4 were selected for the mesocosm study at MSU as they were successful in producing desired plant yield when amended into the Sanborn soil in the pot study. The six media and the PA application rates are summarized in Table 5-4 and the chemical properties of the amendments are presented in Table 5-5.

Table 5-4 Six PA-based soil media and their properties

Media	ID	Dry Bulk density in the box (g/cc)	Application Rate (g/ft^2)
Sanborn	S	1.43	-
Control	C	1.43	-
Control + Carbogrow 3-0-3 at Rate B	CCB	1.43	18.14
Control + Kickstand at Rate B	CKB	1.43	1.81
Control + Sustane 4-6-4 at Rate B	CSB	1.43	22.68
Control + Sustane 4-6-4 at Rate C	CSC	1.43	45.36

Table 5-5 Chemical characterization of proprietary amendments

Property	Carbogrow 3-0-3	Kickstand DG	Sustane 4-6-4
pH	7.4	3.5	6.5
TN (%)	4.55	1.18	4.48
P (ppm)	739	10	2360
K (ppm)	14832	13	21410
Mg (ppm)	1266	19	928
Fe (ppm)	45	540	150

Experiment: The growth experiment was conducted in the UMD (July 3 – Oct 3, 2023) and MSU (July 3 – Oct 13, 2023) research greenhouse facilities. Six identical boxes (each at UMD and MSU) were constructed that are 6 ft in length and 1.5 ft in width. The boxes were inclined at an engineering slope of 2:1 to replicate field conditions (Figure 5.4a). The inside of the boxes was lined with single-sided textured geomembrane to create a friction surface that prevents the soil from sliding down the box given its steep slope (Figure 5.3). Additionally, at the bottom end of each box, a vinyl micro-filter mesh along with a metal mesh gutter guard was securely attached to contain the soil within the box. The soil layer was packed to a depth of 4 inches normal to the base of the box. Each soil was then uniformly seeded with native plant species (a mixture of forbs and graminoids) at the application rate of 36.5 lb/acre. Details regarding the seed mix and their individual application rates can be found in Table 2.4. 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.

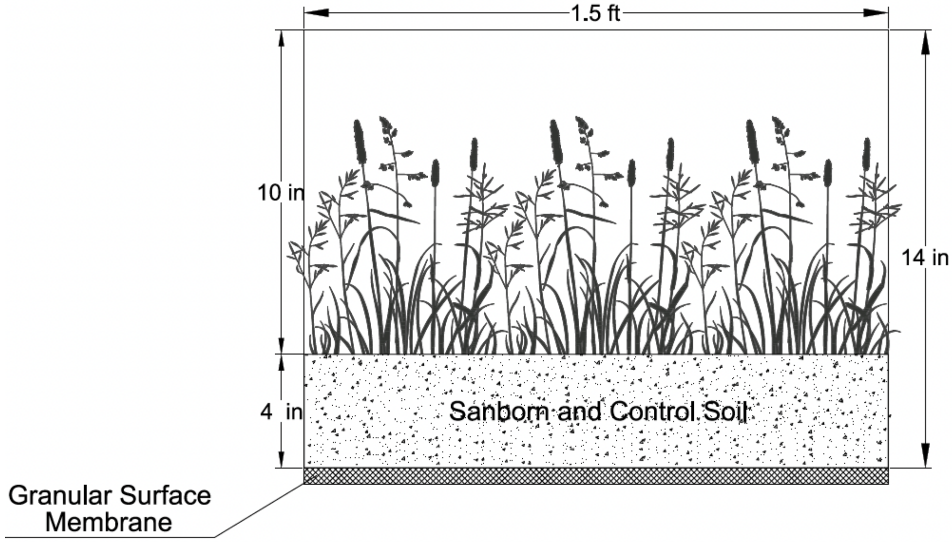


Figure 5.3 Schematic representation of the soil in the box lined with a granular surface textured membrane.

One 0.5 in HH-30 W SQ Fulljet® nozzle connected to the tap water outlet was centered to two boxes, at a height of 9 ft above the ground and used as the rainfall simulator (Figure 5.4). The soils were subjected to a series of 12 weekly rain events at UMD, and 13 weekly rain events at MSU. Applied rainfall depth was 1 in, at an intensity of 4 in/hr.

After each rainfall event, 1L of effluent water was collected as shown in Figure 5.5, using HDPE bottles from each mesocosm box in order to perform laboratory water quality analysis: pH, electrical conductivity (EC), total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP). The pH and the EC were measured by immerging the probe of the pH meter and EC meter, respectively, in the water samples, within 4 hours from collection. The TSS was carried out by filtration using 0.7 µm glass fiber filters, following the EPA Method 160.2 (EPA 1983). A well-mixed, measured volume of a water sample was filtered through the pre-weighed glass fiber filter. The filter was heated to a constant mass at 104 ± 1º C and then weighed. The mass increase divided by the water volume filtered was equal to the TSS in mg/L. At UMD, the unfiltered effluent samples were measured for Total nitrogen (TN) on a Shimadzu SSM-5000A Total Organic Carbon/Total Nitrogen Analyzer. At MSU, TN was measured as the sum of Total Kjeldahl (TKN) and Nitrate (NO_3). For the TKN, the analysis was performed by following EPA Method 350.1 (EPA 1993). The NO_3 was measured by Ion Chromatography, after filtration with 0.22 µm filters. Total Phosphorus was measured by performing digestion using EPA Method 365.1 (EPA 1996) and the Ascorbic acid method using a UV-Vis Spectrophotometer (Perkin Elmer 2015). At UMD, the digested samples were analyzed on a SEAL AQ300 instrument for TP. The list of water quality parameters and their corresponding analytical methods and detection limits are given in Table 5.6 and Table 5.7.

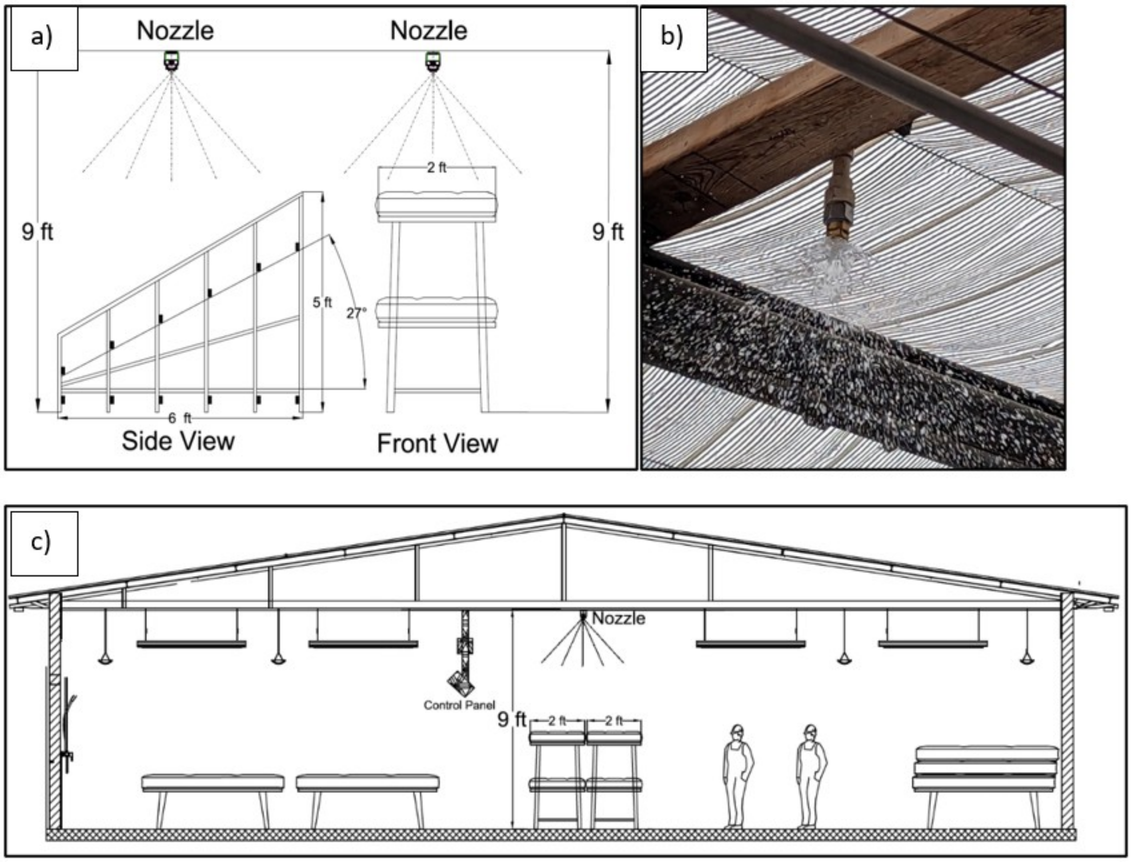


Figure 5.4 (a) Design details of mesocosms along with rainfall simulator, and (b) The HH-30 W SQ Fulljet® used as a rainfall simulator, and (c) Schematic representation of rainfall simulation on the boxes in the greenhouse facility.

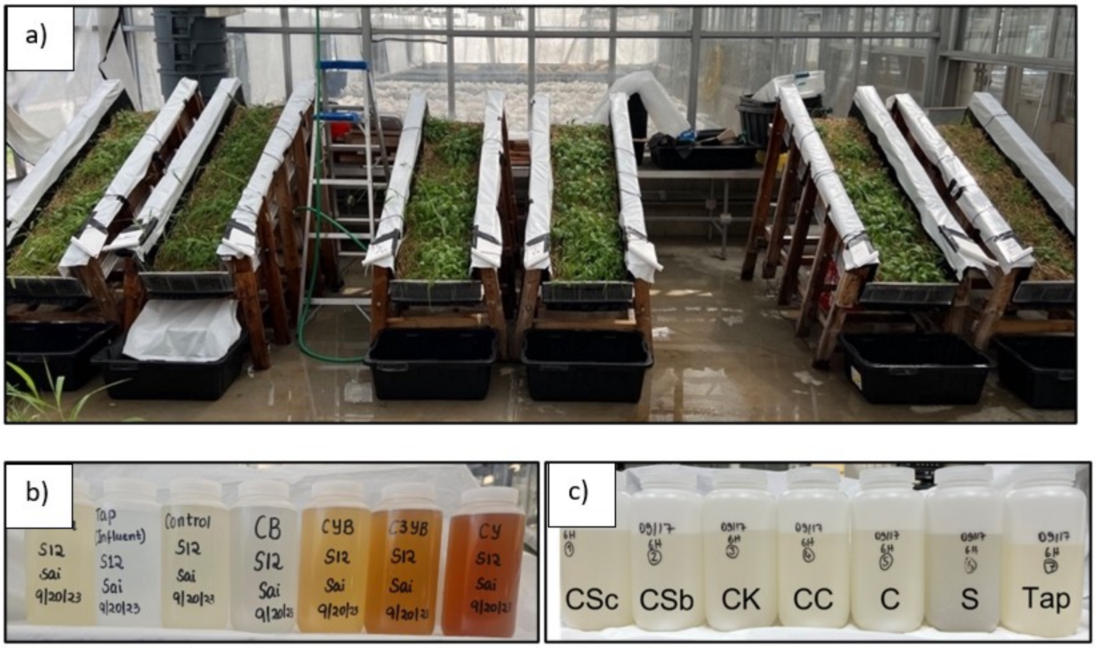


Figure 5.5 (a) Mesocosm experiments conducted in the UMD greenhouse facility, (b) Effluent samples collected into the black totes placed in front of each mesocosm at UMD, and (c) Influent (tap water) and effluent samples collected after simulated rainfall event #12 at MSU.

Table 5-6 Water quality analysis methods, instruments, and lowest standards at UMD

Soil Property	Units	Method	Instrument	Lowest Method Detection Limit
pH	-	EPA method 9040C	VWR symphony B40PCID	2
EC	μS/cm	EPA method 9050A	VWR symphony B40PCID	0.001 μS/cm
TN	mg/L	720°C thermal decomposition - chemiluminescence method	Shimadzu SSM-5000A Total Organic Carbon/Total Nitrogen Analyzer	0.1 mg-N/L
TP	mg/L	Digestion using EPA persulfate method 365.1	SEAL AQ300 Discrete Nutrient Analyzer	0.01 mg-P/L

Table 5-7 Water quality analysis methods, instruments, and lowest standards at MSU

Soil Property	Units	Method	Instrument	Lowest Method Detection Limit
pH	-	EPA method 9040C	VWR symphony B40PCID	2
EC	μS/cm	EPA method 9050A	VWR symphony B40PCID	0.001 μS/cm
TN	mg/L	720°C thermal decomposition - chemiluminescence method	Ion Chromatography System Dionex ICS-1500	0.2 mg-N/L
TP	mg/L	Digestion using EPA persulfate method 365.1	UV Spectrometer	0.01 mg-P/L

Plant Measurements: Pictures were taken weekly starting at 21 days after seeding to estimate the percent green cover (%GC) for the soils both at UMD and MSU. This was done by utilizing the digital image-based software *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. Figure 5.6 presents the image processing steps that were followed for measuring weekly %GC using *Canopeo*.

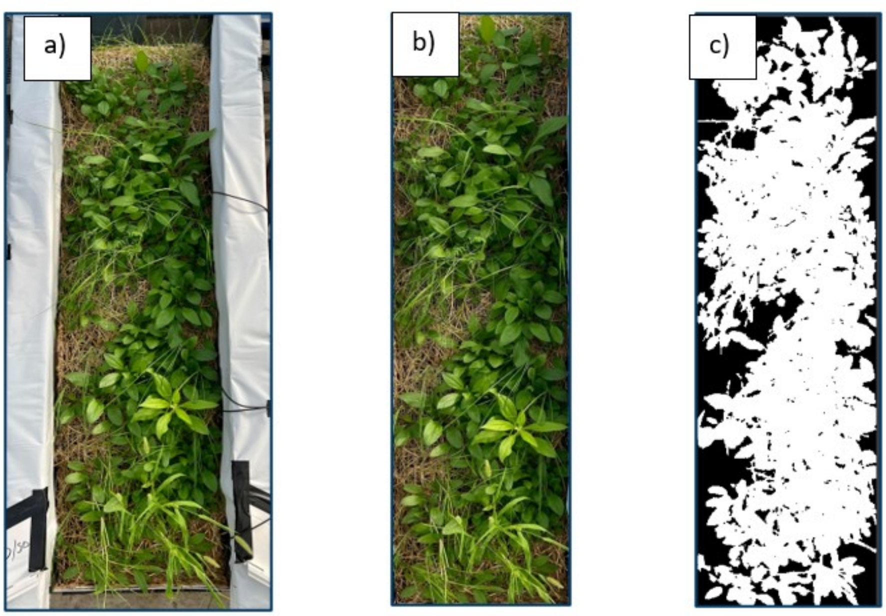


Figure 5.6 Image processing steps followed for %GC analysis in the mesocosms. (a) Original image, (b) Cropped image, and (c) %GC analyzed image.

At the end of the study, the plant matter was snipped at ground level and collected along three 2-ft sections of the box for each media to understand the variability in plant growth along the soil bed. The final plant measurements at UMD included measuring black-eyed Susan (BES) leaf area and dry plant biomass. The total leaf area (LA) of the BES plants was determined on an LI-3100C Area Meter and the area was measured. 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).

Since the PA-soils at MSU predominantly produced grasses, the end-of-study measurements not only collected the plant matter by soil subsections, but also by different plant species. For example, with regards to measuring dry plant biomass, the black-eyed Susans and grasses were separately weighed along each subsection per soil type. The leaf area of the BES plants was also measured at MSU, but the method used Canopeo software. Snipped leaves were positioned on a white platform and a tape measure along with reference red lid were placed at the bottom of the image station. The camera in the image station, with the capability to move both vertically and horizontally, provided consistent image capture conditions, aided by the LED lights. Images, including the reference red lid and leaf from each soil sub-section were captured (Figure 5.7). Similar to the %GC estimation, LA was also calculated based on the % green against a known white background area.

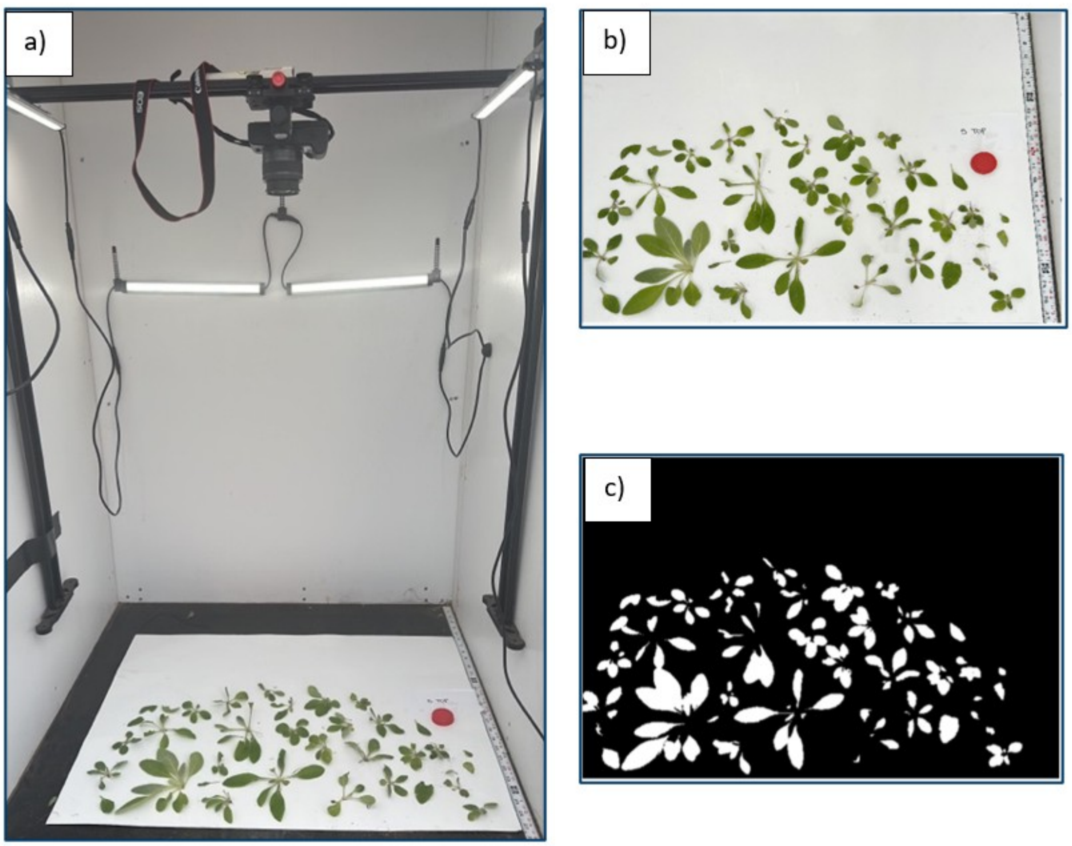


Figure 5.7 Conditions created for taking consistent images with LED lights, white platform, and tape measure. (a) capturing images of the snipped leaves on the platform, and (b) output obtained by software analysis of the image.

Given the abundance of grass species in the PA-soils at MSU, it was crucial to also include plant height measurements besides biomass and LA. Grass height was measured by taking the sum of three measurements, equally spaced from the top to the bottom of the mesocosm box. Grasses from each sub-section of the mesocosms were measured using a metal ruler and a scaled cutting mat (Figure 5.8). The resulting data included the maximum and average grass heights produced in each mesocosm.

Figure 5.8 Scaled cutting mat used for determining grass heights.

Statistics

Since there were no experimental replicates, three sub-samples were collected from each sample and subjected to water/soil/plant quality analysis for QA/QC purposes. 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.

5.2 Results

5.2.1 Water Quality

5.2.1.1 Background Constituents

As evidenced by data pertaining to soil pH and EC, it is discernible that an 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. This observed trend was likewise reflected in the effluents of the soil samples. The pH of soil and soil amendment mixtures followed the order: CB > CYB > C3YB > C > CY > S, while the EC displayed this trend as: CY > C3YB > CYB > S > C > CB, particularly during the initial rainfall events (Figure 5.9and Figure 5.9b). In addition, the pH of all soil effluent samples increased initially after the first few rainfall applications, eventually reaching a plateau by the end of the test. This increase occurs because of the plant uptake of nutrients (e.g., uptake of NO3 releases OH- ions (Bolan et al. 1991; Lea-Cox et al. 1996), and as vegetation establishes, the inherent (or amendment driven) buffering capacity of the soil stabilizes the pH (Geng et al. 2022; Jien et al. 2015). 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. Results from the MSU experiments also showed that the pH values increased during the initial rainfall event for all water samples and then became constant, reaching a plateau by the end of the test (Figure 5.9a). The EC also decreased overtime. The use of Kickstand increased the pH values greater than that of Sustane and Carbogrow amendments. It is worth noting that the EC of the tap water in the MSU facility was higher than the EC of the tap water in the UMD institution. The EC of the water from enriched soils, such as Sustane and Kickstand were higher than the EC values obtained from the control plot (Figure 5.9b).

At the onset of the experiments, the soil mixes were initially dry, which caused lower runoff volumes compared to subsequent rainfall events (2-12). However, these initial conditions led to higher sediment content in the runoff samples in the first 1 inch of rainfall. As the experiment progressed, the OAs 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 (Figure 5.9c). 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. However, the concentrations of TSS dropped down to 9.7 mg-TSS/L by the end of the test. Results from the experiment performed at MSU showed that the TSS was continuously decreasing during the test (Figure 5.9c). Effluent samples from Sustane (CSC) and Kickstand (CKB) had TSS higher than Carbogrow at the beginning of the study. The maximum TSS after the first rainfall event was 423 mg-TSS/L for Sustane at a rate of C, 595 mg-TSS/L for Kickstand, and 34.5 mg-TSS/L for Carbogrow. Control and Sanborn alone had 122 mg-TSS/L and 80.1 mg-TSS/L, respectively, after the first rainfall event. At the 12th week rainfall event, an increase in the level of TSS was observed at the MSU experiment setup. Thus, one more rainfall event was carried out to ensure the system was stabilized. It was observed that the suspended solids decreased again on the 13th week rainfall event and the test ended.

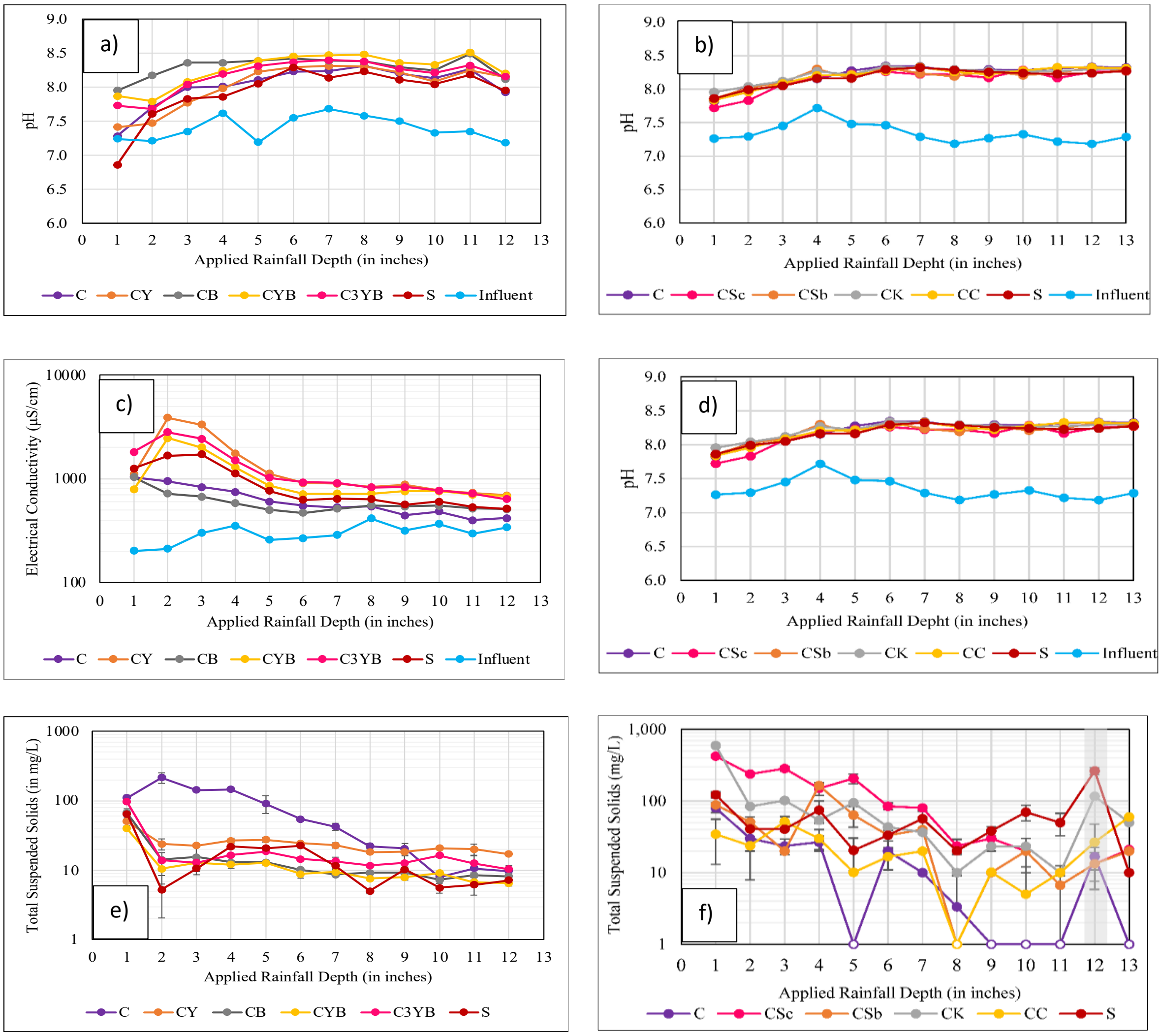


Figure 5.9 pH values measured after each simulated rainfall at UMD and MSU (a and b, respectively); Electrical Conductivity (µS/cm) measured after each simulated rainfall at UMD and MSU (c and d, respectively); Total Suspended Solids (mg/L) measured after each simulated rainfall at UMD and MSU (e and f, respectively)

Legend: S: Sanborn; C: Control (Sanborn + Sand); CY: Control + Yard-waste Compost; CB: Control + Biochar; CYB: Control + 50% Yard-waste Compost + 50% Biochar; C3YB: Control + 75% Yard-waste Compost + 25% Biochar
CSC: Control + Sustane Rate C; CSB: Control + Sustane Rate B; CKB: Control + Kickstand Rate B; CCB: Control + Carbogrow Rate B.

5.2.1.2 Nutrients in soil effluents

The data on nitrogen and phosphorus from the collected runoff samples are presented in Figure 5.10 and Figure 5.11. In the case of nitrogen, the original topsoil (Sanborn) demonstrated a low C:N ratio (14.2:1) and a total nitrogen of 0.17% (typical to agricultural soils; Horneck et al. (2019)) in the soil. As a result, the runoff total nitrogen concentrations in the early stages of the rainfall events from S exceeded 100 mg-N/L. The incorporation of inorganic sands to make the soil control 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 experiment. The contrasting impacts of yard-waste 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 and 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. The C:N ratio of the soils is a robust indicator that controls the losses of mobile nitrogen. The total mass exported (in mg) of NO_x-N and N from the soil runoff were plotted against their respective soil C:N ratio, which noted an inverse relationship (a decaying power function) with a coefficient of determination R^2 = 0.88 and 0.93, respectively. Carbon-rich materials like biochar can increase this C:N ratio leading to the immobilization of the mineralizable N (NO_x or NH_4) in the soil as microbes utilize it for their nutritional needs (Adams et al. 2005). At MSU, the total nitrogen showed a decreasing trend for all effluent samples collected from each plot. The nitrogen from the effluent (tap water) was below the detection limit. Water samples from Carbogrow (278 mg-N/L) had the highest TN value. After the first rainfall event, the nitrogen concentration decreased to < 1 mg-N/L in all effluent samples, except the Sustane at rate c effluent (1.43 mg-N/L). Results from the MSU investigation were close to those measured by the UMD institution for Control and Sanborn specimens.

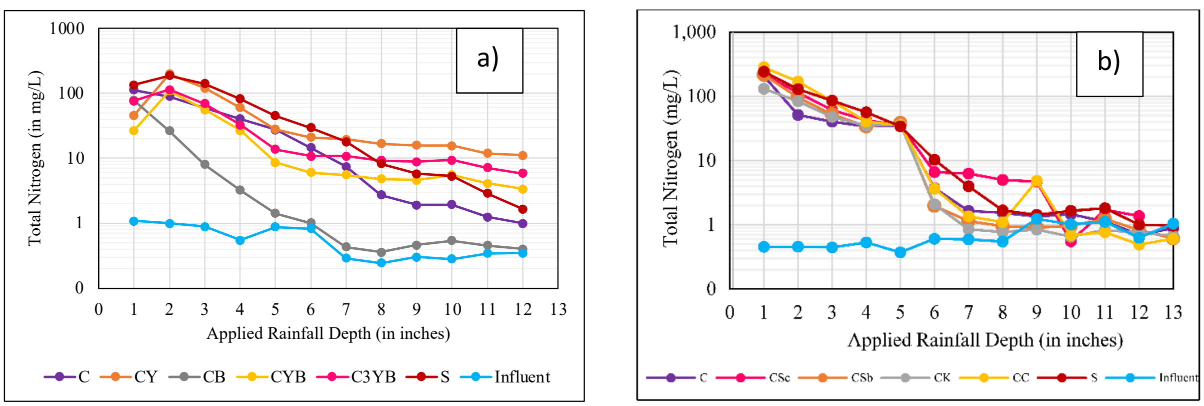


Figure 5.10 Changes in concentrations of TN (in mg/L) in soil effluents with increase in rainfall depth. (a) UMD and (b) MSU.

Legend: S: Sanborn; C: Control (Sanborn + Sand); CY: Control + Yard-waste Compost; CB: Control + Biochar; CYB: Control + 50% Yard-waste Compost + 50% Biochar; C3YB: Control + 75% Yard-waste Compost + 25% Biochar

CSC: Control + Sustane Rate C; CSB: Control + Sustane Rate B; CKB: Control + Kickstand Rate B; CCB: Control + Carbogrow Rate B.

Soils S, C and CB retained phosphorus, releasing concentrations lower than the influent TP in their steady state (Figure 5.11a). A first flush of P was noticed in the S and C effluents. The former (S) attained a rapid steady state after the first 1 in of rainfall, while the latter (C) gradually reduced and levelled off after applying 10 in of rainfall. In contrast to nitrogen, which consistently decreased over rain events, phosphorus (especially from that of soils with compost present in it) did not exhibit a distinct pattern but maintained consistent elevated releases throughout the study. 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. Yet, 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.

Several factors contribute to P release into soil runoff. 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 the pH conditions 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 5) under which conditions the phosphates in the soil typically participate in inorganic complexation with secondary minerals (e.g., Ca) (Tunesi et al. 1999). Although biochar and compost both contain similar M3-P contents, the former’s carbon content is 4.2 times more than that of compost (Table 4.3). High carbonaceous materials can lead to a greater demand for phosphorus from the soil microbes, which immobilizes this nutrient (similar to N) in the soil, thereby affecting organic matter decomposition rates (Roberts et al. 2012). The combination of high surface area/porosity, high pH, carbon content and stability offer P retention advantages to the biochar amendment over compost. Therefore, this increase in C:P ratio when biochar is incorporated with compost reduced the P runoff losses from CYB and C3YB soils compared to CY. Soil with Carbogrow and Sustane retained phosphorus, releasing concentrations lower than the influent TP, mostly for all duration of the test (Figure 5.11b). As also noticed in the results reported by UMD, in contrast to nitrogen, which consistently decreased over rain events, phosphorus did not exhibit a distinct pattern but maintained consistent elevated releases throughout the study. The use of Sustane in soil showed peaks in TP leaching. TP concentrations in Carbogrow effluent were lower than the concentration of phosphorous released by the Sustane effluent (CSc) ranged between 0.03-0.37 mg-P/L and 0.06-0.79 mg-P/L, respectively. TP released by soil mixed with Kickstand and Carbogrow were close to each other for all duration of the test (ranged between 0.02-0.61 mg-P/L and 0.03-0.42 mg-P/L, respectively). The TP range from Sanborn, Control (Sanborn + Sand) and influent water samples from MSU was close to that reported by UMD.

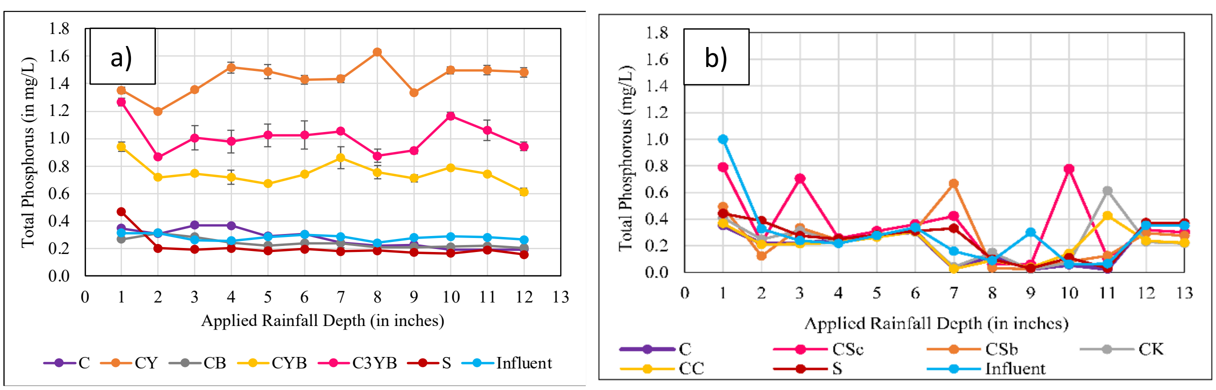


Figure 5.11 Changes in concentrations of TP (in mg/L) in soil effluents with increase in rainfall depth (a) UMD and (b) MSU.

Legend: S: Sanborn; C: Control (Sanborn + Sand); CY: Control + Yard-waste Compost; CB: Control + Biochar; CYB: Control + 50% Yard-waste Compost + 50% Biochar; C3YB: Control + 75% Yard-waste Compost + 25% Biochar
CSC: Control + Sustane Rate C; CSB: Control + Sustane Rate B; CKB: Control + Kickstand Rate B; CCB: Control + Carbogrow Rate B.

5.2.2 Vegetation Growth

Figure 5.12a illustrates the weekly progress 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%. The least effective soil (CB) covered only 40.6% of the 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%. Regarding the temporal changes of vegetation growth at MSU (Figure 5.12b), the sequence of coverage on soil-amendment mixes was revealed as CSB>S>CCB> CKB>C>CSC. CSB soil emerged as the most productive and fertile soil. The plant species showed early maturity and robust growth, spreading across a wide area, and achieving a green coverage of 70 %. S soil media produced a GC of 64% at the end of the growth study. Its performance, surpassing the control soil (C), can be attributed to its higher organic matter (OM), lower pH level, and higher cation exchange coverage (CEC). CCB reached 55% GC by the end of week 12, producing 24% more green coverage (GC) than the unamended control soil (C). Moreover, CCB demonstrated significant growth, especially in the first 3 weeks, producing growth 2 to 4 times earlier/faster compared to other amendments. This early considerable growth can be attributed to the significant prevalence of weed species. By the corresponding week, weed species were removed, and GC reached levels comparable to S, CKB, and CSB by week 4. CKB reached 53% GC by the end of week 12. It outperformed the unamended control media in both early and long-term growth, producing 19% more GC than C soil. CSC exhibited the weakest plant growth, both in the long term and during the initial weeks of the test. The GC lagged the other amendments, S, and even the unamended C media. By week 9, the GC was nearly 20%, eventually reaching 40% by the end of week 12. This shows 4% less green coverage than the unamended control media and 24% less than the S soil. The reasons behind the poor performance of this mixture include the steep slope of 2:1, soil susceptibility to sliding with rainwater application, which breaks plant roots and hinders growth.

The dry biomass was collected 91 days after seeding from each box (Figure 5.12c). The total biomass yield was the highest in C3YB (62.9 g), followed by CY (61 g), CYB (53.2 g), S (50 g), C (41 g), CB (17.5 g). This shows that the coverage alone does not determine the density of the plant matter growing in the soil. 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, resulting in a significant difference of 23.25 in^2 between the two soils. The findings from the pot study 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. Compost and biochar addition in equal proportions (CYB) resulted in a 30% increase in biomass and 11.7% expansion in the leaf area of the BES plant 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 2-ft sections: top, middle, and bottom. The biomass production in the top layer of the soil bed was lower compared to the middle and 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 S soil, the biomass was 44% higher in the middle and 24% higher in the bottom than in the top section. In the amended soils, the variation in plant biomass across the soil sections was less than 23%. The leaf area of the BES plants was also more in the bottom and middle sections compared to the top across all soils. This could be attributed to the moisture (and nutrient) retention capabilities of the amended soils, ensuring a more uniform plant production, even on steep slopes like a 2:1 slope.

Regarding the dry biomass collected from the MSU mesocosms (Figure 5.12d), the total biomass achieved was the highest in CSB (43.5 g), followed by S (40 g), CCB (37.5 g), C (28.5 g), CKB (26 g), CSC (23 g). CSB soil, treated with NPK-rich amendment, emerged as the most effective amendment for supporting biomass growth. CSB increased biomass by 52% compared to C soil. BES species thrived on CSB soil more than other mixtures, indicating that this media is conducive to growth, particularly for the BES plant. S soil, characterized by a lower pH and higher OM content, resulted in greater biomass accumulation, 1.4 times, compared to the C soil. CCB performed better compared to C, resulting in 32% more biomass accumulation. CKB soil performed almost equally with C, although it resulted in less biomass accumulation compared to S soil. More specifically, there was 8% and 30% less accumulation than C and S soil, respectively. However, CSC yielded 35% less biomass than C and 40% less biomass than S soil. Regarding plant health, soil amendments aimed at enriching the soil do not consistently provide positive effects and it should be noted that the critical factor is the level of amendment application (Alloway 1995). The reduced performance of CSC can be associated with the potential for the applied rate to lead to "excessive" or "luxury consumption" by plants. In this case, nutrient absorption by the plant does not influence yield.

Regarding the leaf area obtained at MSU (Figure 5.12f)**,** CSB had the greatest BES leaf area, producing 4.76 ft^2 (685 in^2) compared to other soils. This was 4 and 5 times greater than that of the unamended C soil and S soil with high organic matter content, respectively. Furthermore, the leaves in this mesocosm, healthy and wide in shape, had grown and matured earlier than in the other scenarios. C and S were observed to have insufficient BES leaf area, yielding 1.17 ft^2 (168 in^2) and 0.98 ft^2 (142 in^2), respectively because grass species predominantly grew more in these environments (Figure 5.12f). Although BES species did not thrive on the upper portion of the S soil, it achieved a leaf area nearly as large as the C. CKB soil achieved 1.37 ft^2 (197 in^2) leaf area, 18% more leaf area than unamended C soil, and 39% more leaf area than the S soil. CSC soil was poor in terms of green coverage and biomass accumulation performed best after CSB. It produced a leaf area of 1.47 ft^2 (212 in^2), which was 26% more than the C and 49% more than S. The less biomass accumulation, despite efficient leaf area, can be attributed to the presence of large and broad leaves although the mass was lower. CCB yielded a leaf area of 0.90 ft^2 (130 in^2), which is less than the other mesocosms. Nearly 70% of its biomass (29.5 g) was attributed to the weight of grass. Given that 30% of the biomass (8 g) comprises BES species, the leaf area performance was comparatively lower than in the other scenarios (Figure 5.13).

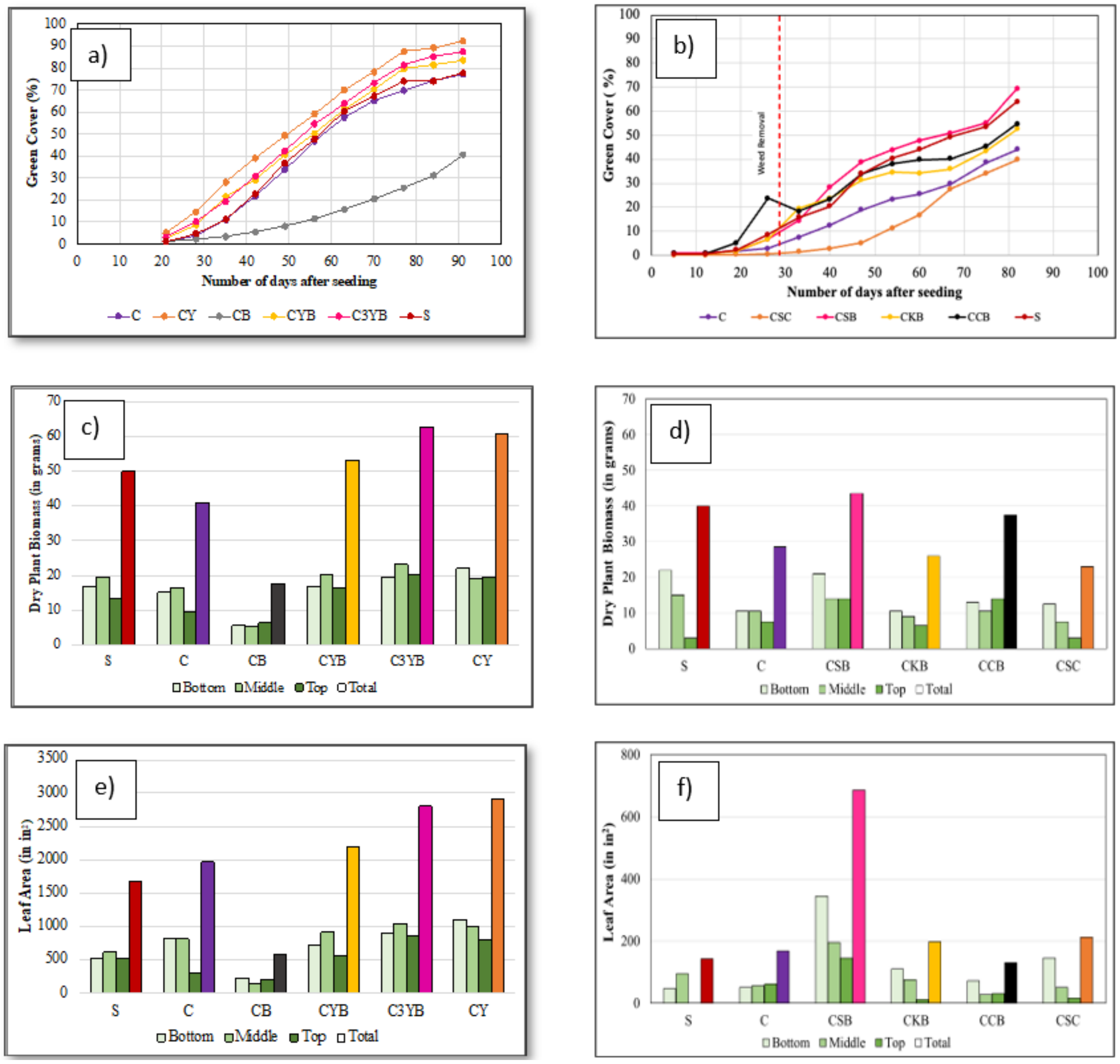


Figure 5.12 Weekly vegetation coverage (as % Green) from UMD and MSU (a and b, respectively); End-of-the-study dry plant biomass (in grams) from UMD and MSU (c and d, respectively); and End-of-study leaf area of the BES plants (in in^2) from UMD and MSU (e and f, respectively).

Legend: S: Sanborn; C: Control (Sanborn + Sand); CY: Control + Yard-waste Compost; CB: Control + Biochar; CYB: Control + 50% Yard-waste Compost + 50% Biochar; C3YB: Control + 75% Yard-waste Compost + 25% Biochar
CSC: Control + Sustane Rate C; CSB: Control + Sustane Rate B; CKB: Control + Kickstand Rate B; CCB: Control + Carbogrow Rate B.

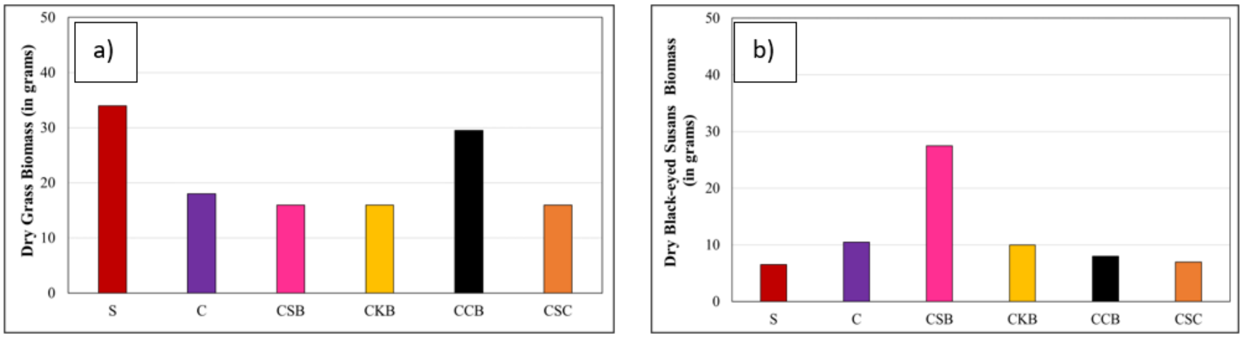


Figure 5.13 Dry biomass at MSU. a) Grass, and (b) Black-Eyed susans.

Legend: S: Sanborn; C: Control (Sanborn + Sand); CSC: Control + Sustane Rate C; CSB: Control + Sustane Rate B; CKB: Control + Kickstand Rate B; CCB: Control + Carbogrow Rate B.

The average grass height in the MSU studies was 16 inches and the maximum plant height reached 31 inches in S soil (Figures 5.14a and Figure 5.14b). Notably, an exceptional grass height of 46 inches was recorded as well. Therefore, S stands out as the most effective in terms of average grass height. The average grass height was 10 inches, with the maximum grass height reaching 20 inches in C soil where sand was mixed with soil to reduce organic matter content. CSB produced an average grass height of 13 inches, and the maximum grass height reached 19 inches. Despite the dominant growth of BES species and lower grass biomass in this scenario, there was a 22% increase in average grass height compared to the C soil. Thus, the impact of the proprietary application is clearly shown in CCB soil. The average plant height of 14 inches was 40% greater than that of C soil (10 inches), and the maximum plant height of 35 inches was 1.8 times greater than C soil (20 inches). CKB soil yielded the same average plant height as the control mesocosm (10 inches), while the maximum plant height (28 inches) was 36% greater than the C soil. CSC soil achieved an average plant height of 15 inches and a maximum plant height of 26 inches. The average and maximum grass heights were 48% and 28% greater than C soil, respectively.

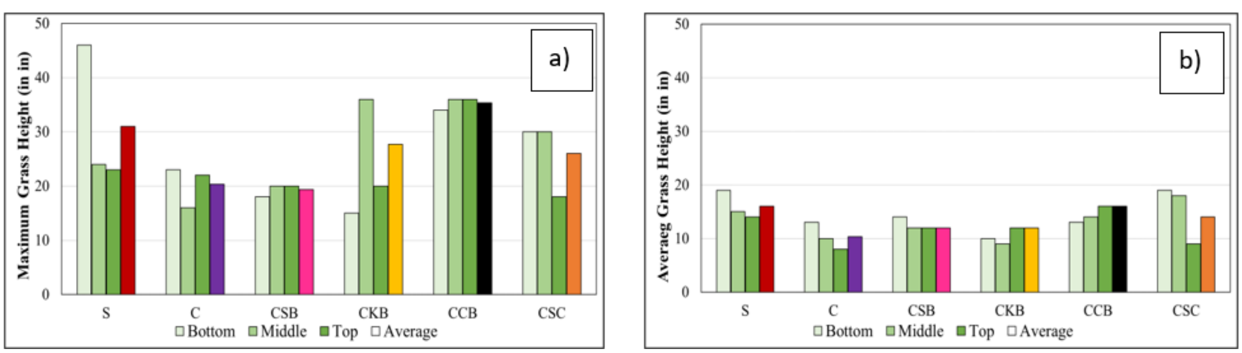


Figure 5.14 End of study grass heights at MSU. (a) Maximum grass heights, and (b) Average grass heights.

Legend: S: Sanborn; C: Control (Sanborn + Sand); CSC: Control + Sustane Rate C; CSB: Control + Sustane Rate B; CKB: Control + Kickstand Rate B; CCB: Control + Carbogrow Rate B.

5.3 Chapter Conclusions

Biochar and yard-waste compost organic amendments (UMD) and proprietary soil amendments (MSU) were mixed into a control soil to understand their effects on water quality and vegetation growth in a scaled up mesocosm experiment that mimicked field conditions.

OAs influence on Vegetation Growth

1. Biochar addition to the control soil (CB) stunted plant growth (57% less biomass and 70% less leaf area compared to reference soil-C).
2. The singular addition of compost to the control soil (CY) resulted in 49% more biomass and leaf area than reference soil-C.
3. Compost and biochar mixtures (CYB and C3YB) also promoted plant growth, with improvements more pronounced with higher compost proportions in the soil, outperforming S, C and CB soils.
4. Plant growth across the soil bed indicated that amended soils yielded more uniform coverage than unamended control soil.

PAs influence on Vegetation Growth

1. CSB emerged as the most effective amendment for biomass accumulation, showing a performance 52% higher than C soil. CCB exhibited a 32% increase, whereas CKB amended media accumulated nearly the same amount of biomass as the C. Notably, CSC resulted in 21% less biomass accumulation compared to C soil.
2. CSB had the most significant impact on leaf area, producing four times more leaf area than the C soil. CKB and CSC led to 18 and 26% more leaf area than the control, respectively. In contrast, CCB exhibited less leaf area than C soil, primarily due to a substantial portion of its biomass being comprised of grass species (70%).
3. CSB improved the GC by 57% greater than C soil. CCB and CKB outperformed (by 24% and 19%) the C soil, whereas CSC did not seem to have an impact on the %GC.
4. All amendments generated greater (20% to 50%) grass heights than C soil.

OAs influence on Water Quality

1. Over time, the pH levels in all soil effluents increased and attained a steady state, whereas EC and TSS decreased with each rainfall event.
2. Water quality data revealed that the biochar-amended soil (CB) caused lower N export to the effluent compared to other study soils. Conversely, the yard-waste amendment caused greater release of N from the soils.
3. An inverse relationship between effluent N and soil C:N ratio was observed. Soils with a higher C:N ratio (e.g., CB) had lower N concentrations in the effluent, and vice versa.
4. The influent (tap water) phosphorus of ~0.3mg-P/L was effectively retained by the S, C and CB soils throughout the study period. However, compost incorporation caused greater phosphorus loss in the effluent, with higher P export correlating to increased compost content in the soil.

PAs influence on Water Quality

1. Over time, the pH levels in all soil-PA mixture effluents increased and attained a steady state, whereas EC and TSS decreased with each rainfall event.
2. Water quality data revealed that the PA Kickstand caused lower N leaching to the effluent compared to the use of Sustane and Carbogrow. The Carbogrow amendment caused greater release of N from the soils.
3. Soil mixed with Carbogrow and Sustane retained phosphorus, releasing concentrations lower than the influent TP. Phosphorous concentrations from Carbogrow effluent were lower than those released by Sustane. TP released by soil mixed with Kickstand and Carbogrow followed similar trends to each other throughout the duration of experiments.

Chapter 6: Field Study

6.1 General Overview

Plants and soils have a symbiotic link to each other as they are key to ecosystem dynamics, water flow, erosion control, food, and agriculture. Roadside vegetation is essential for improving the functional and environmental aspects of roads and assists in managing stormwater runoff and reducing soil erosion, which lessens flooding and promotes groundwater recharge. For this reason, establishing vegetation alongside roads is a critical component of green infrastructure and stormwater control. As the Minnesota Department of Transportation (DOT) aims to improve road safety, environmental sustainability, and the quality of life for state residents, organic amendments (OA) and fertilizer-like products (proprietary amendments) have been used for roadside vegetation establishment.

Organic amendments have been used for combating soil erosion and providing effective landscape management in vegetation establishments. Decomposition of organic waste results in compost, which is beneficial for soil structure, water retention capacity, and soil aggregate stability (Faucette et al., 2004). Soil structure is improved by binding between organic matter and clay particles via cation bridges and through stimulation of microbial activity, root development, and plant growth (Farrell & Jones, 2009; Gao et al., 2010). Rivers et al. (2021) conducted a study to determine the efficiency of soil improvement measures to decrease runoff and improve water quality alongside roads, suggesting that adding compost to compacted urban soils may significantly enhance the biological and physical characteristics of the soil, which in turn influence stormwater infiltration and interception. Apart from compost, fertilizers supply vital nutrients for plant development, which can enhance soil cover and lower the danger of erosion (Durán Zuazo and Rodríguez Pleguezuelo, 2008). A dense and healthy vegetation cover that absorbs rainwater, reduces runoff velocity, and boosts soil infiltration capacity is encouraged by an adequate supply of nutrients (Gyssels et al., 2005).

The application of proprietary fertilizer amendments also affects biomass accumulation and vegetation growth to prevent soil erosion. Fertilizer-like substances (proprietary soil amendments) are combined with topsoil to increase crop growth potential. These unique mixes are crucial for fostering nutrient availability and ideal soil conditions since they frequently include a combination of organic and/or inorganic substances intended to treat certain soil and nutrient deficits. Ettebb et al. (2020) studied the performance of vegetation coverage using perennial grasses with various Nitrogen-Phosphorus-Potassium (NPK) treatments. Sudan grass and Rye grass treated with NPK combinations showed improved nitrogen absorption and soil fertility (Li et al., 2010). Compost, fertilizers, and proprietary amendments are examples of additives that should be assessed for their environmental impact, considering potential pollutants and their effects on soil and water. Eutrophication (an excessively high nutrient content) in water and groundwater contamination can result from leached nutrients, particularly nitrogen and phosphorus (Carpenter et al., 1998). Waterbodies may be harmed, and nutrient enrichment could worsen due to N and P releases to surface waters. Thus, it is important to examine the effects of amendment type and application rates on water quality to reduce potential environmental impacts.

This study aims to evaluate the efficacy of two soil amendments that performed the best in the greenhouse pot study (Chapter 4) and greenhouse mesocosm study (Chapter 5) of this project, specifically, yard-waste compost (an organic amendment) and Sustane 4-6-4 (a proprietary amendment), on vegetation growth and water quality parameters at a field scale, under natural rainfall conditions and slope. To achieve this, nine experimental plots, each measuring 19 feet high and 8 feet wide, were constructed with a 1:3 slope to simulate roadside embankments. A runoff collection system was constructed beneath the plots using PVC pipelines to collect both runoff and infiltrated water after rainfall events. The study involves analyzing traditional water quality parameters (pH, EC, and TSS), and nutrient constituents (TN and TP), and assessing the long-term performance of the amendments on vegetation growth. The collective results of this study provide practicable recommendations for the safe and beneficial use of OAs and PAs in roadside projects. Additionally, these findings suggest the potential application of OAs and PAs in topsoil remediation, which may help control erosion, promote vegetation growth, and improve stormwater quality.

6.2 Soil and Amendment Properties

Field Soil: Physical properties, including the plastic limit (PL), liquid limit (LL), and particle size distributions of the field soil, were assessed according to ASTM D6913, ASTM D4318, and ASTM D7928 standards. Table 6.1 displays these properties and the soil classifications as per the Unified Soil Classification System (USCS) and the United States Department of Agriculture (USDA). Figure 6.1 shows the particle size distribution of the field soil.

Table 6-1 Physical properties and classification of soil

Soil	%Gravel	%Sand	%Silt	%Clay	LL (%)	PI (%)	USCS	USDA
Field Soil	2	37	45	16	27	9	CL	Loam

Notes: Clay ≤ 2 µm, LL: Liquid limit (ASTM D 4318), PI: Plasticity index, CL: Low-plasticity clay

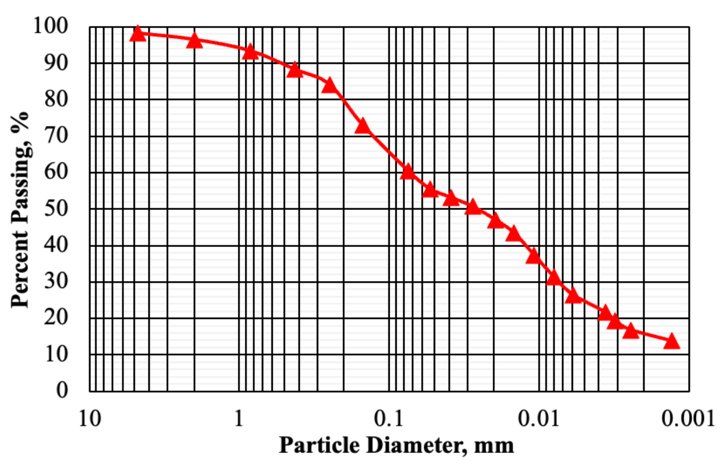


Figure 6.1 Particle size distribution curve of the field soil.

Table 6.2 summarizes soil pH, electrical conductivity (EC), organic matter content (OM), phosphorus, and potassium. pH and OM (Loss of ignition at 455°C) were evaluated according to ASTM 4972 and AASHTO T267 Method. Phosphorus (P) was extracted through the Bray-1 Method.

Table 6-2 Chemical and nutrient analysis of field soil

Soil	pH	OM (%)	CEC (meq/100g)	NO_3-N (ppm)	NH_4-N (ppm)	P (ppm)	K (ppm)
Field Soil	6.95±0.6	2.03±0.6	17.05±0.45	51±2	2±0.0	22.3±7.4	114±7.6

Proprietary Amendment (Sustane 4-6-4): Considering the importance of essential macronutrients and micronutrients for plants, NPK-rich amendment (Sustane 4-6-4) has exhibited promising results in the pot experiment (Chapter 4) and mesocosm experiment. Collectively, the results of these studies help guide the field study (Task 5.1). PAs were applied at increasing application rates of the nutrients in Tasks 4.1 and 4.2. Given the promising results in applications rate B (22.68 g/ft^2) and C (45.36 g/ft^2), this amendment was selected for the field study. Proprietary amendment properties including pH, total nitrogen (TN), phosphorus (P), potassium (K), magnesium (Mg), and iron (Fe) were analyzed at MSU Soil and Plant Nutrient Laboratory. The chemical properties of the Sustane 4-6-4 are presented in Table 4.2.

Organic Amendment (Yard-Waste Compost): Compost made from yard waste (YW) was one of the two organic amendments (OAs) selected for previous studies at the University of Maryland (UMD). The compost was sourced from Specialized Environmental Technologies-The Mulch Store. This OA was added to soil to enhance its organic matter content in pot experiments (Chapter 4) and mesocosm experiments. Amendment properties including pH, electrical conductivity (EC), organic matter percentage (OM%), carbon (C), and nitrogen (N) were analyzed at UMD Environmental Engineering Laboratories to evaluate its usage for soil fertility. Details of the soil chemical analysis are provided in Table 4.3.

6.3 Test Sections Preparation

6.3.1 Site Location and Plot Dimensions

The research team built test sections using the best mix design combination of organic amendment (OA) and proprietary soil amendment (PA), as determined through the greenhouse experiments. In Chapter 4 (pot study), OA was applied to soil to achieve target organic matter (OM) levels of 5%, 7.5%, and 10%, while Chapter 5 (mesocosm study) focused on a target OM of 6% for soil-OA blends. According to the MnDOT specifications manual, the manufacturer's recommended fertilizer rate (Rate B) should be used for topsoil. Rate A was defined as half of Rate B, and Rate C as double Rate B to assess the effects of PA content under different nutrient conditions in greenhouse studies. Soils amended with yard-waste compost (target OM of 6%) and Sustane 4-6-4 at rates B and C exhibited enhanced plant growth compared to other amendments used in the greenhouse studies. Nine test sections were constructed at MnRoad Facility: three control soils with non-treated poor-quality soil with low organic matter content (2.03±0.6%), three PA-amended soils, and three OA-amended soils. Each plot had a width of 8 ft and a length of 19 ft. The slope of the shoulder was approximately 1:3. The height of the topsoil was 4 inches, consistent with the greenhouse pot (Chapter 4) and greenhouse mesocosm studies (Chapter 5), stating that the fertile layer (topsoil), 4 inches in height, corresponds to the minimum depth of MnDOT Spec 3877 *Common Topsoil Borrow.* Figure 6.2 shows the location of the test site and the dimensions of the plots installed.

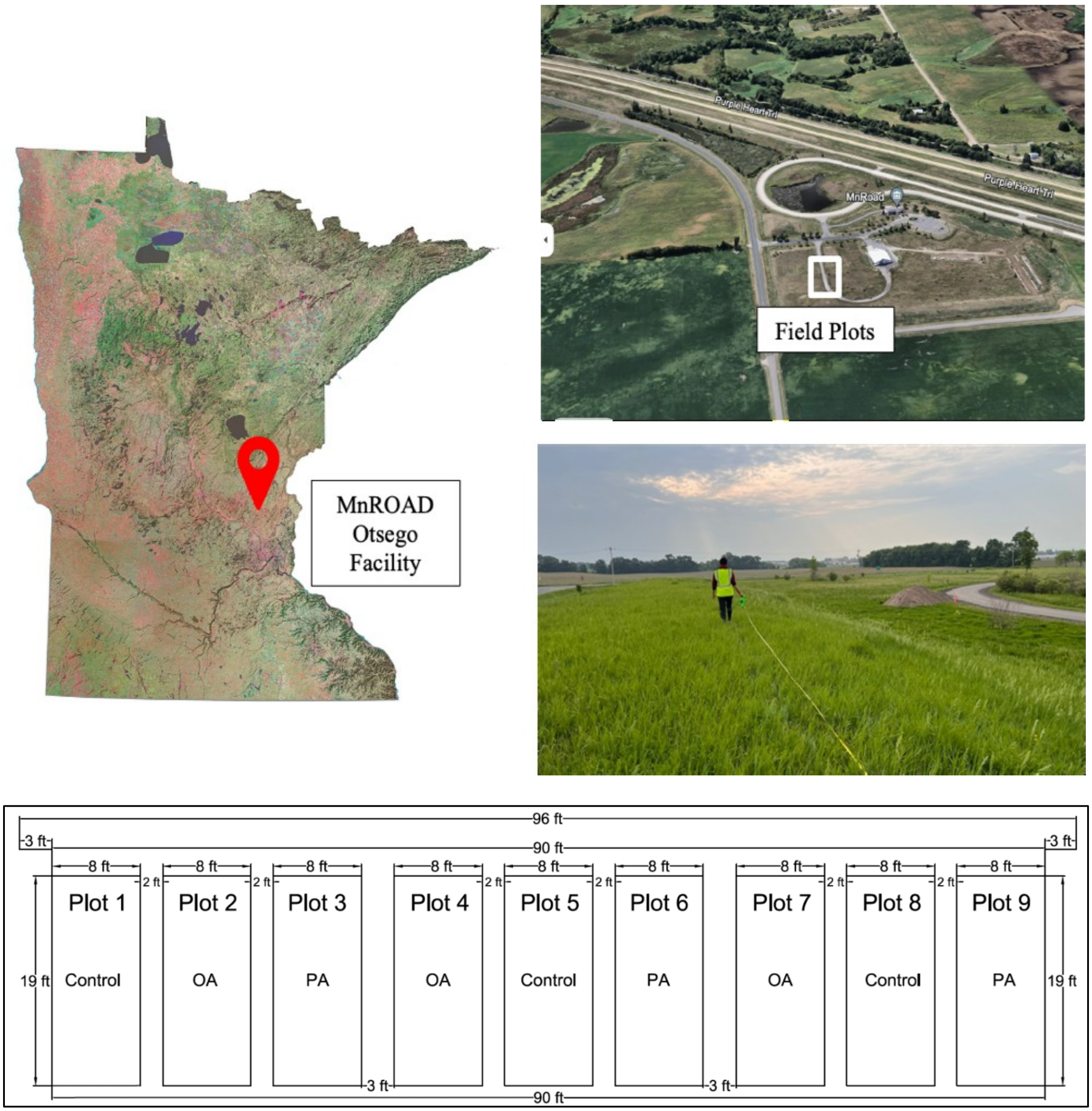


Figure 6.2 Site location and plots.

6.3.2 Field Plots Construction Phases

Boundaries of plots were delineated before setting them up in the field. A skid loader removed the existing vegetation and excavated a 4-inch layer of soil from each plot. Figure 6.3 shows the removal of existing vegetation and the excavation of soil.

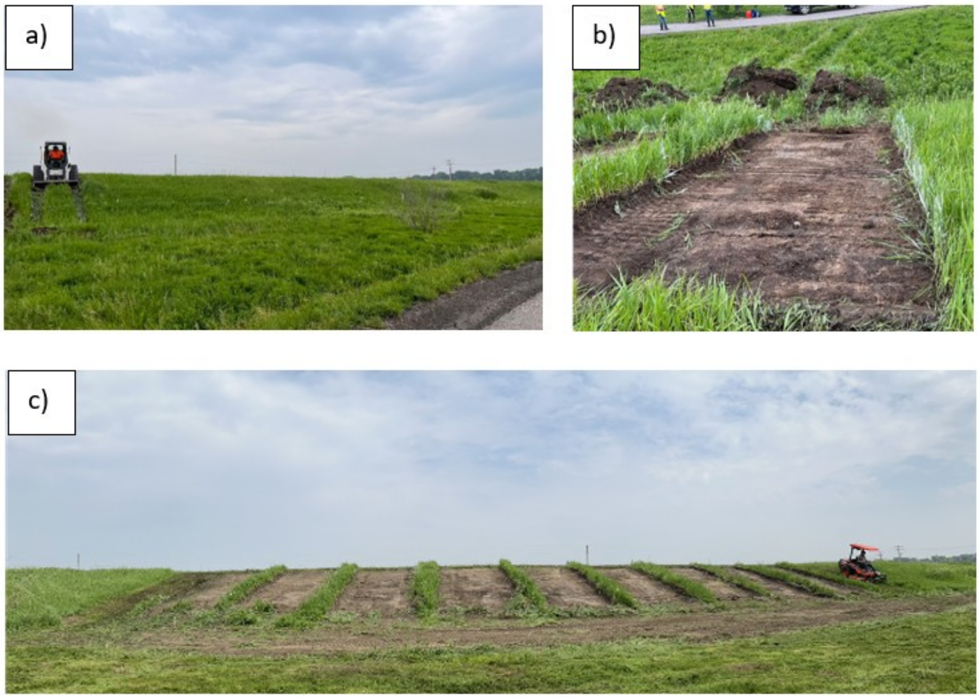


Figure 6.3 (a) Excavation of plots, (b) removal of the existing vegetation, and (c) final excavated plot's view.

With knowledge of the OM content of both the soil and OAs, bulk density and OM content data for the soil and OAs (as presented in Table 4.3) were utilized to calculate the necessary quantities of soil and OAs required to attain the target OM level (7%) in field OA plots. Equation 1 was used to calculate the amount of yard-waste compost (OA) to add to soils. Table 6.3 reports the parameters used in the calculations. The volume of each plot (V_{OA} + V_S) was 50.67 ft^3 (8 ft width, 19 ft length, and 4-inch height).

$$\frac{V_{OA}+V_s}{V_s} = \frac{\rho_s(\theta_t - \theta_s)}{\rho_{OA}(\theta_{OA} - \theta_t)} \qquad \text{(Equation 1)}$$

Table 6-3 Parameters to calculate the amount of OA (Yard-waste compost)

Bulk Density of OA, ρ_{OA} (pcf)	48
Bulk Density of soil, ρ_s (pcf)	90
OM of OA, θ_{OA} (%)	30
OM of soil, θ_s (%)	2
Target OM of the soil-OA blend, θ_t (%)	7

For each OA plot, approximately 36 ft^3 (1.33 yd^3 of soil and 14.67 ft^3 (0.54 yd^3) of yard-waste compost were used. After placing the calculated amount of soil and OA in the OA plots, compost-soil was uniformly mixed using a skid loader with tillage equipment. To prevent cross-contamination, the equipment was cleaned before placing material in the next plot. The equipment used and the blending operation are shown in Figure 6.4.

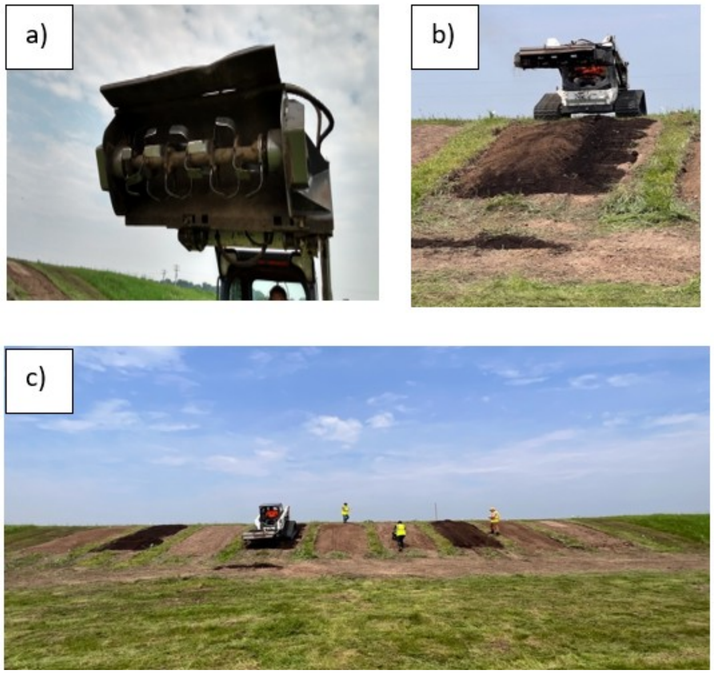


Figure 6.4 (a) Skid loader with tillage equipment, (b) placing the amendments (OA) and topsoil with a skid loader, and (c) overall site preparation.

In field applications of proprietary amendments (PAs), the methodology diverged from that employed for organic amendments (OAs). Unlike the OA procedure, where soil and OA volumes varied with application rates, the amendment Sustane 4-6-4 at rate C (45.36 g/ft^2)—demonstrated as one of the most effective in pot and mesocosm studies—was used. Given the predetermined plot dimensions and application rates, the calculated amount of amendment was uniformly applied across the plots using a fertilizer spreader. Table 6.4 shows the amount of the Sustane 4-6-4 amendment applied to produce 45.36 g/ft^2. The photos in Figure 6.5 depict the distribution of proprietary amendment in PA plots.

Table 6-4 Parameters to calculate the amount of PA (Sustane 4-6-4)

Width of test section, B (ft)	8
Length of test section, L (ft)	19
Area of test section, A (ft^2)	152
Application rate, R (g/ft^2)	45.36
Amount of amendment for each plot, AxR (g)	6895

Figure 6.5 Distribution of proprietary amendment in PA plots with fertilizer spreader.

In Control and PA-amended soil plots, topsoil was placed to a depth of 4 inches within the excavated zone. For OA-amended plots, topsoil and compost were incorporated into a 4-inch excavation and thoroughly blended using tillage equipment. Following the application of the amendment to the PA plots, all plots were raked before seeding to achieve seed-bed contact ensuring that seeds were properly in contact with soil, facilitating water absorption, germination, and growth. The Minnesota Native Landscape (MNL) mesic prairie seed mix (15.05 lbs/acre) was uniformly distributed in each plot by hand-broadcasting (Appendix C). After raking and seeding, double-layered straw erosion control blanket with biodegradable netting -S32BD, sourced from *ECBVERDYOL*, was placed on top of the plots to minimize erosion. Figure 6.6 illustrates the raking operation for each plot and the distribution of the seed mix.

Figure 6.6 (a) Raking operation to create seed-bed contact, (b) distribution of seed mix through hand-broadcasting, and (c) application of erosion control blankets.

6.3.3 Preparation of Runoff Collection Systems

To facilitate runoff collection, a pipe system was established at the base (one each) of the control, OA, and PA plots (plots 1, 4, and 9, respectively). The system is comprised of 2 6-inch diameter pipes, each 8 feet in length, which were horizontally bisected. A trench, 4 inches deep and with a slight gradient to ensure efficient water flow, was excavated for the installation of the pipes (refer to Figure 6.7a and Figure 6.7b). Runoff from the plots was in the pipes and conveyed to barrels that were partially embedded in the soil (refer to Figure 6.7c).

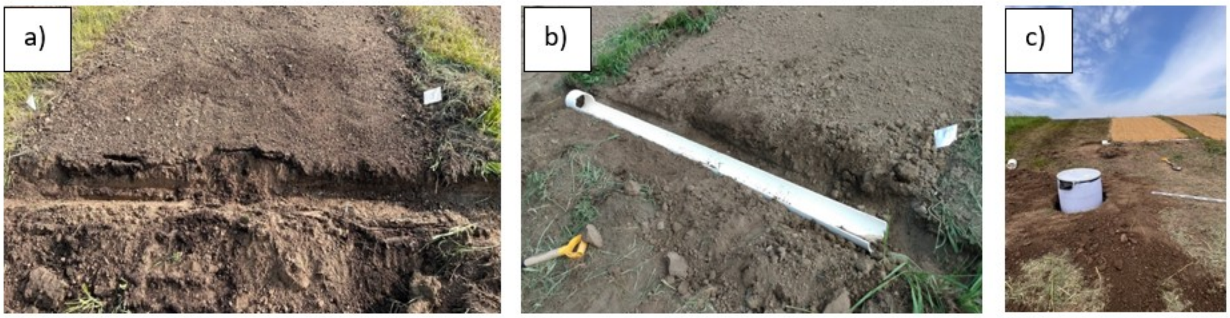


Figure 6.7 (a) 4-inch excavated trench, (b) 6-inch pipe that cut in a half placed in the trench, and (c) placing the barrels in the excavated hole.

The half-pipe placed in the trench was tied down into the soil by using plastic stakes and nylon rope (Figure 6.8a). Elbows were used to connect the half pipe to the full pipe to reach the barrel. (Figure 6.8a and Figure 6.8b). To direct the water into the barrels, a metal plate was placed on top of the barrels (Figure 6.8c).

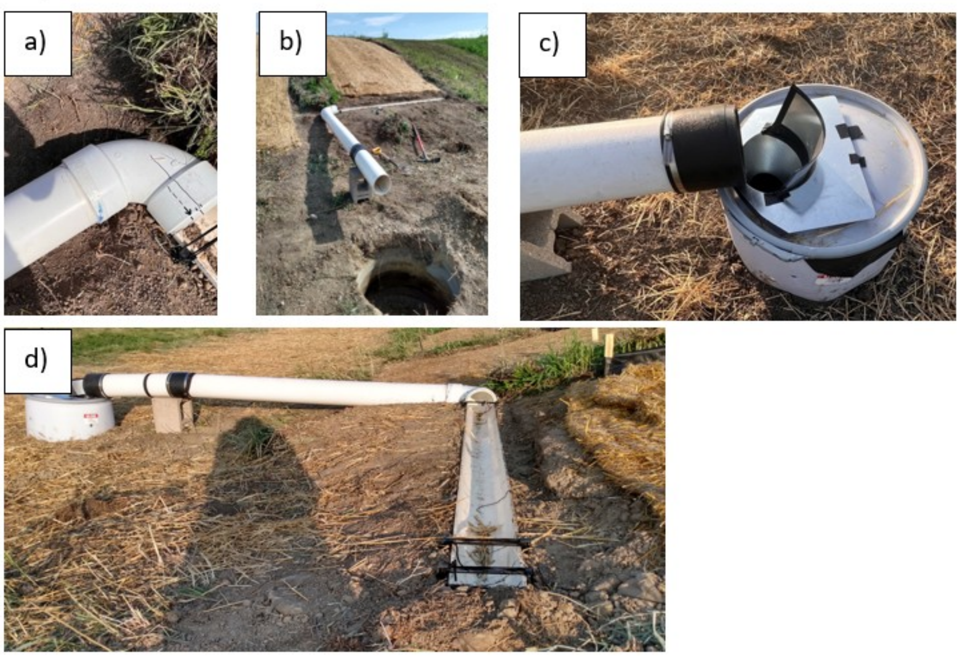


Figure 6.8 (a) Elbow connection between half-pipe and full pipe (6" diameter), (b) full pipe connection up to hole for barrels, and (c) steel plate element placed on the barrels, and (d) final view of the runoff collection system.

6.4 Vegetation Growth Measurements

Two sets of growth experiments (Cycle 1 between July 1, 2023, and Oct 25, 2023, and Cycle 2 from April 22, 2024 – October 25,2024) have been conducted in the field study. Throughout these cycles, which also comprised seasonal transitions, the influence of the applied organic and proprietary amendments on plant growth and water quality was systematically assessed. Key parameters, including vegetation coverage, plant height, above-ground biomass, below-ground biomass (root density), and soil bulk density, were measured and monitored to evaluate the effects of the amendments on vegetation growth in Cycle 1. During Cycle 2, measurements of vegetation coverage and plant height have been conducted. At the end of cycle 2, additional assessments were performed, including measurements of above-ground biomass, bulk density, root density.

6.4.1 Image Analysis for Vegetation Coverage

Pictures were taken weekly starting 14 days after seeding to estimate the percent green cover (%GC) for the soils in the field. This was done by utilizing the digital image-based software *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 border of field plots on *Adobe Scan* before calculating %GC and extraneous elements and features across images were excluded. Figure 6.9 presents the image processing steps that were followed for measuring periodically %GC using *Canopeo*.

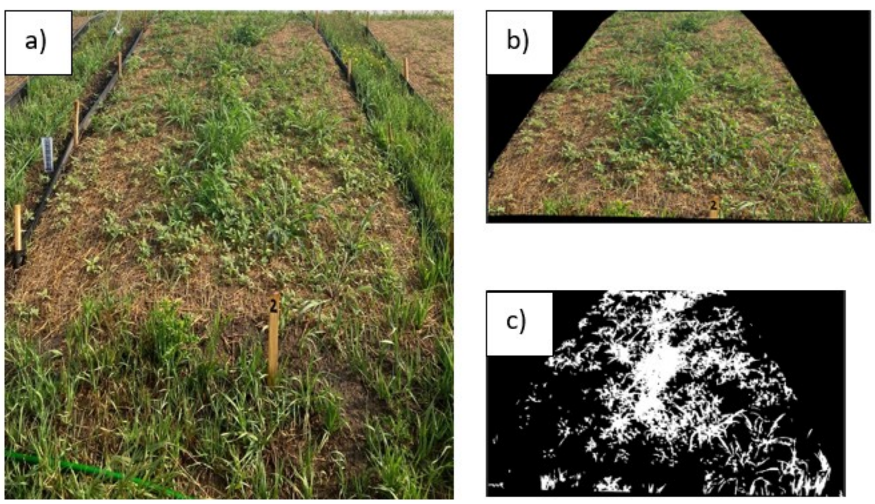


Figure 6.9 Image processing steps followed for %GC analysis. (a) original image, (b) cropped image, and (c) %GC analyzed image.

At the field site, two Brinno TLC200Pro Time Lapse construction cameras were placed inside birdhouses attached to a cemented pole, as depicted in Figure 6.10a. These cameras were configured to capture one image per day, providing data at regular intervals. The cameras, positioned to cover a 90-foot width of the field plots, as shown in Figure 6.10b. Vegetation coverage was quantified through image analysis methods developed by the UMD team and crosschecked with Canopeo analysis. The procedures for image capture, segmentation, feature extraction, and vegetation classification followed the decision tree algorithm approach outlined by

Owen et al. (2020). Images were analyzed using Matlab (2018b), with pixels examined for color, texture, and gradient orientation to categorize vegetation into green, straw/dormant, or bare soil.

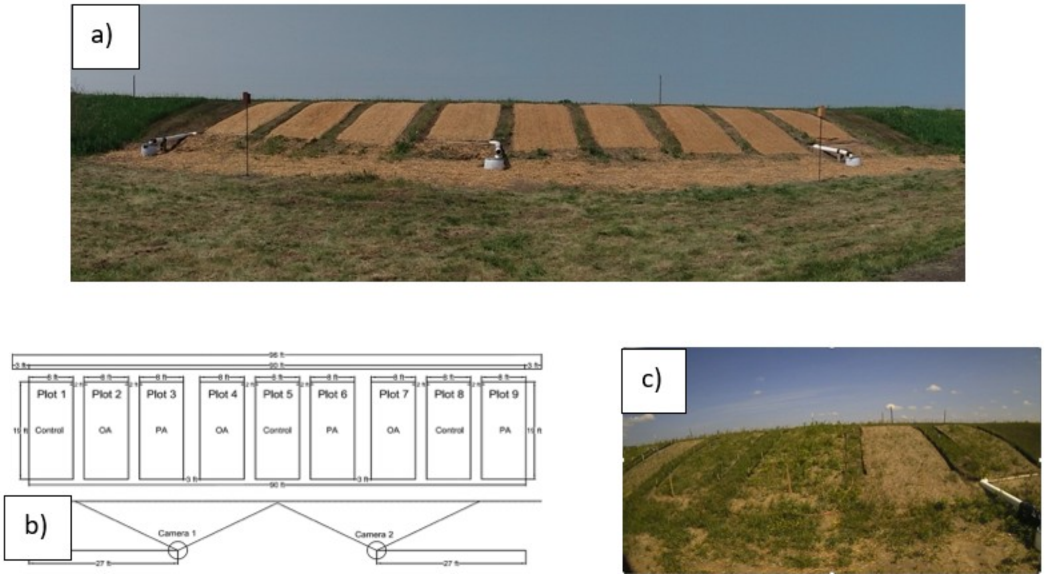


Figure 6.10 (a) Positions of birdhouses for cameras, (b) camera capture areas, and (c) image captured through camera.

6.4.2 Plant Heights

Given the high density of grass species in the first cycle, it was crucial to include plant height measurements. Grass height was determined by averaging two measurements taken at equally spaced areas from the top to the bottom of each plot. A minimum of six measurements were collected per plot, with at least two measurements taken from the upper, middle, and lower sections. A ruler was used for all measurements. The resulting dataset comprised both the maximum and average grass heights observed in each plot. Figure 6.11 depicts the height measurement procedure at the end of the first cycle.

Figure 6.11 Grass height measurement procedure with ruler in the field plots.

6.4.3 Above Ground Biomass

After 140 days of growth, plant samples were collected from six locations (two from the bottom, middle, and top) within each plot using an 18x12-inch plastic frame to quantify species biomass. Above-ground biomass, excluding weeds, was measured. The procedure involved harvesting the vegetation at the soil level, weighing and transferring it to brown paper bags, shipping to Michigan, and oven-drying at 50°C (122°F) for 48 hours. Following the drying process, the plant material was weighed to determine the dry biomass, following USDA NRCS (2022) guidelines. Figure 6.12 shows the above-ground biomass procedure for field plots at the end of Cycle 1.

Figure 6.12 (a) Locations of biomass measurements, (b) vegetation in the frame area before clipping, and (c) removed vegetation in the frame.

6.4.4 Below-Ground Biomass (Root Density)

A total of 54 samples were extracted from 9 field plots, ensuring that at least 6 samples (2 from the bottom, 2 from the middle, and 2 from the upper portion of each plot) were collected from each plot on October 23, 2023 (140 days after seeding). To determine the weight of plant roots in a given area of soil, root biomass measurements were conducted on the soil samples taken height and 4 by using a core sampler tool (2 inches in diameter and 4 inches in height) during the field visit in October. The weight and volume of the soil cores were recorded in the field. Then, the extracted cores were soaked in water at MSU labs and, after stirring them thoroughly, the mixture of soil and roots was sieved to obtain the root (Figure 6.13).

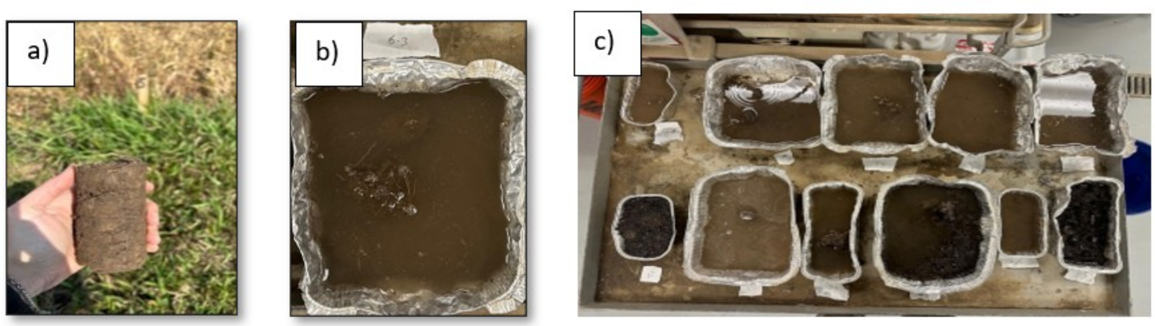


Figure 6.13 (a) Extracted sample from field plots, (b) soaked sample in water with roots, and (c) samples soaked in the water.

6.4.5 Bulk Density

Bulk density is crucial for vegetation health as it influences soil aeration, root growth, water infiltration, and nutrient availability. High bulk density often leads to soil compaction, which restricts root expansion, reduces soil porosity, and limits nutrient access; however, lower bulk density typically supports better root development, and enhanced nutrient availability, all of which contribute to healthier and more productive plant growth (Wolkowski and Lowery (2008), Tracy et al. 2011, Shah et al. 2017). For this reason, given that bulk density serves as an indicator of soil compaction and structural quality of soil, a total of 54 bulk density samples (2 inches in diameter and 4 inches in length) were collected, with 6 samples obtained from each plot. Figure 6.14 shows core collection locations along with a photo of an extracted soil sample.

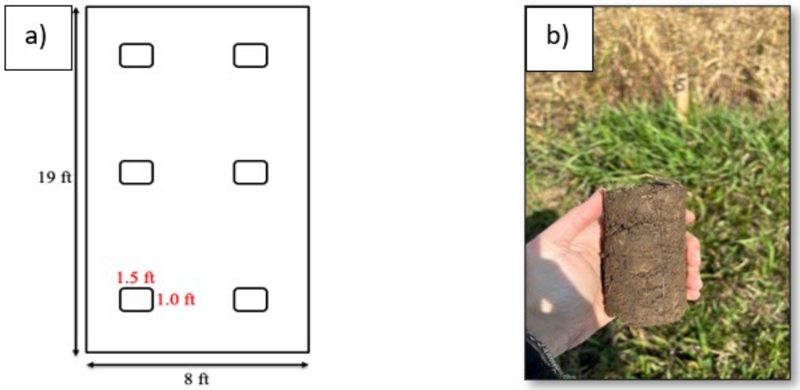


Figure 6.14 (a) Location of samples extracted from plots, and (b) extracted sample from field plots.

6.5 Water Quality Analysis

Runoff water samples collected through the runoff collection pipes and barrels after all rainstorm events between June 2023 and October 2023, and between June 2024 and July 2024, were analyzed for pH, electrical conductivity (EC), total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP). The pH and the EC were measured by immerging the probe of the pH meter and EC meter, respectively, in the water samples. The TSS was carried out by filtration using 0.7 µm glass fiber filters, following EPA Method 160.2 (EPA 1983). A well-mixed, measured volume of a water sample was filtered through the pre-weighed glass fiber filter. TN was measured as the sum of Total Kjeldahl Nitrogen (TKN) and Nitrate (NO_3-N). For the TKN, the analysis was performed by following EPA Method 351.2 (EPA 1993). NO_3-N was measured by Ion Chromatography after 0.22 µm filtration. Total Phosphorus was measured by digestion using EPA Method 365.1 (EPA 1996) and the ascorbic acid method using a UV-Vis Spectrophotometer (Perkin Elmer 2015). Figure 6.15 shows the pipes and barrel system used to collect water from the rainfall events and an example of water samples collected from each plot. The list of water quality parameters and their corresponding analytical methods and detection limits are given in Table 5.7.

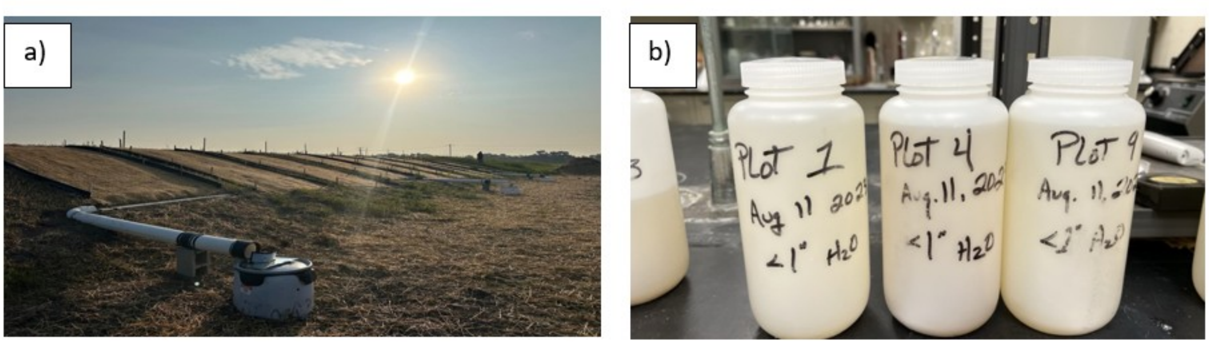


Figure 6.15 (a) Runoff and infiltrated water collection barrels and pipes, and (b) effluent samples collected after a rainstorm event.

Statistics: In the absence of experimental replicates, three sub-samples were extracted from each primary sample for water, soil, and plant quality analysis to ensure quality assurance and control. Where applicable, the mean and standard deviation were calculated to assess variability among method replicates. To evaluate the relationship between two variables, Pearson's correlation coefficient (R) and regression analysis were conducted, with a significance level set at $\alpha = 0.05$, to determine the probability value (P-value).

6.6 Results

6.6.1 Vegetation Growth (Coverage and Height)

In this section, the data collected for green coverage and height from Cycle 1 and Cycle 2 are analyzed. Observations from Cycle 1 indicate a broader diversity of grass species in the field, whereas Cycle 2 data highlight a predominance of forb-flowering plants. The irrigation system was set to supply water when temperatures were high, and rainfall rare. Three oscillating sprinklers were placed to ensure uniform water distribution across the target area. Two rain gauges are located at different locations in the irrigated area to monitor water application and natural rainfall.

Cycle 1 Vegetation Coverage: Vegetation coverage measurements have started from 14 days after seeding (June 2023) until August 2024. Regarding the temporal changes of vegetation growth in the field, the sequence of coverage on plots was OA>PA>Control. OA soil emerged as the most productive and fertile soil. The grass species showed early maturity and robust growth, spreading across a wide area, and achieving an almost 100% green coverage as of the end of July 2023. During the first two months of the study (June-July 2023), soils amended with OA and PA demonstrated earlier growth compared to the control. By the third week of July 2023, both OA and PA soils achieved over 80% coverage relative to the control soil. However, by the first week of August 2023, green coverage began to decline due to yellowing induced by high temperatures. A mowing operation was conducted in the second week of August 2023, which subsequently stimulated renewed plant growth. The presence of a higher proportion of forb species in the OA soil led to a more pronounced decrease in plant coverage. Following the mowing, OA soil exhibited a more pronounced growth acceleration compared to other soils. By the end of the first cycle (October 2023), vegetation coverage across all soil types converged to nearly the same values. Figure 6.16 presents the temporal changes in vegetation coverage in Cycle 1.

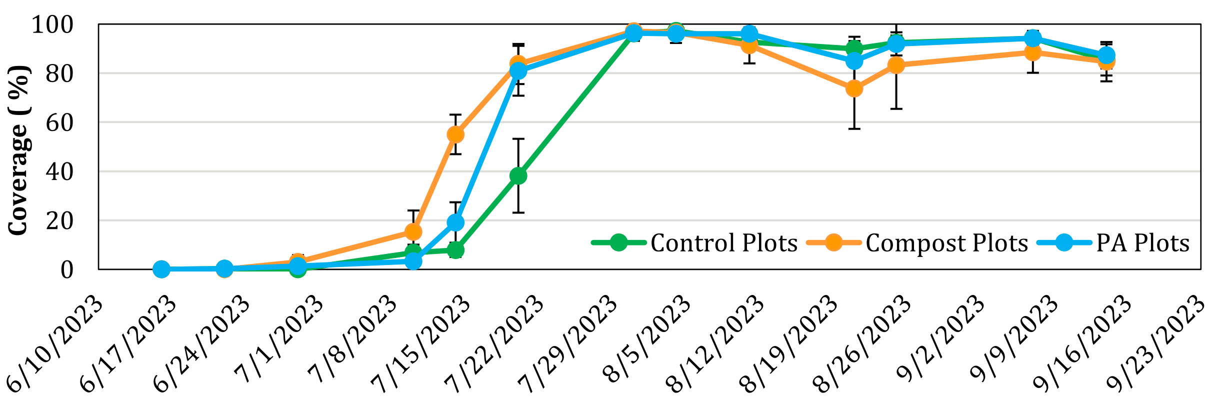


Figure 6.16 Green coverage analysis in Cycle 1.

Cycle 2 Vegetation Coverage: The second growth cycle initiated in May 2024. Unlike the first cycle, where grass species were predominant, the second cycle saw forb-flowering plants become more dominant within the plots. Due to the extensive coverage of flowering plants, the calculated coverage values advanced more rapidly in the second cycle. As observed in the first cycle, OA-amended soil demonstrated earlier growth and proved to be effective. During the first month of the second cycle, the OA soil achieved 94±4 percent coverage, compared to 80±12 percent in PA-amended soil and 70±17 percent in the control. By the first week of June, coverage had increased to 97±2 percent in OA soil, 87±7 percent in PA soil, and 80±3 percent in the control. By the end of June, green coverage across all plots approached 100 percent. Both cycles demonstrated that OA and PA amendments facilitated more rapid growth compared to the control. Figure 6.17 and Figure 6.18 show the temporal changes of vegetation coverage in Cycle 2 and Cycle 1-2 together, respectively.

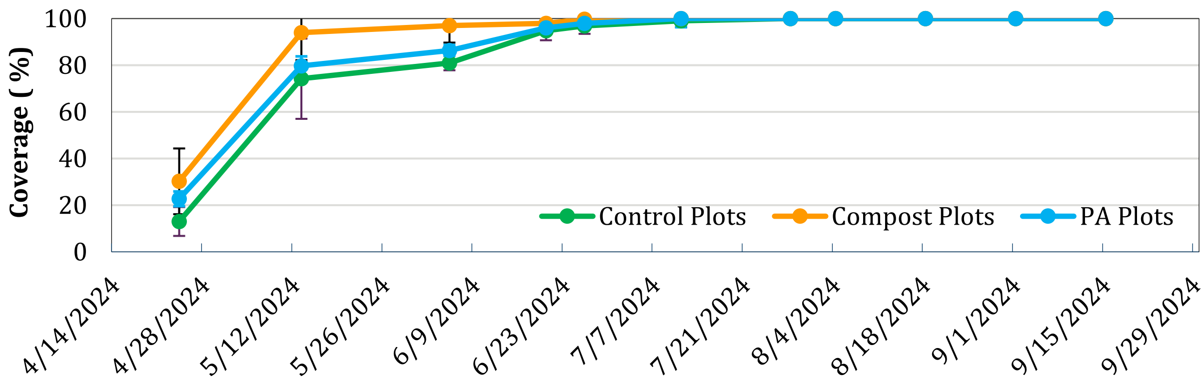


Figure 6.17 Green coverage analysis in Cycle 2.

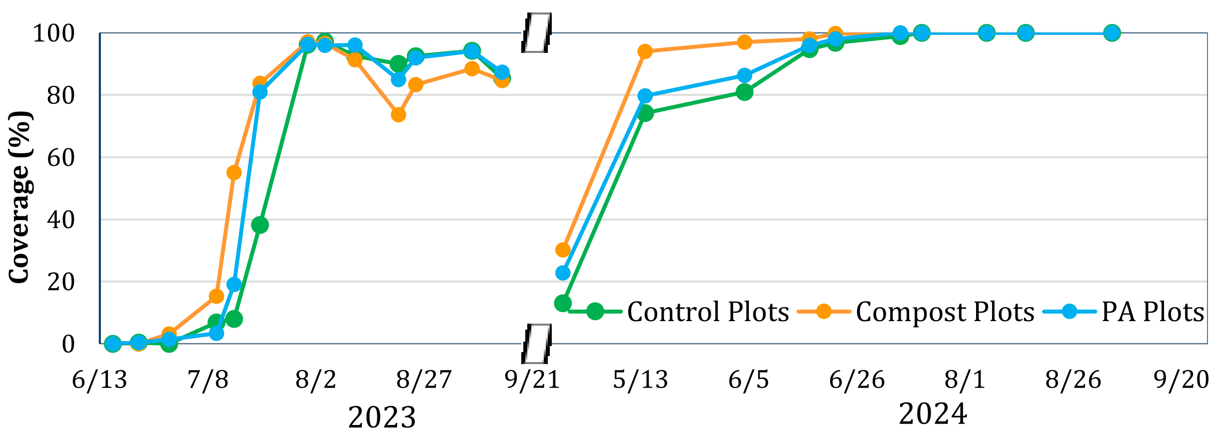


Figure 6.18 Green coverage analysis in Cycle 1 and 2 together. The timeline between October 2023 and March 2024 indicates the period of dormancy (winter season).

Cycle 1 Grass Heights: The MNL seed mix, which included grass and forb-flowering plant species, predominantly yielded grass species during the first growth cycle. Specifically, barnyard grass (*Echinochloa*) and bristle grass (*Setaria Verticillate*) were identified in the field. The average grass height was 16±1 inches, with a maximum height of 25±1 inches at the end of 1st cycle 140 days after seeding. PA soil had an average grass height of 13±1 inches and a maximum height of 19±2 inches, whereas control soil produced an average height of 17±2.5 inches, with a maximum height of 24±0.5 inches in the same time period (140 days after seeding). This indicates that OA soil is the most effective in promoting maximum grass height, showing 32% greater maximum heights than PA; however, control soil achieved 5% greater average grass heights than OA soil and 30% more than PA soil. The reduced plant height observed in PA and OA-amended soils during Cycle 1 is attributed to the density and abundance of weed species present. Figure 6.19 shows the maximum and average grass heights.

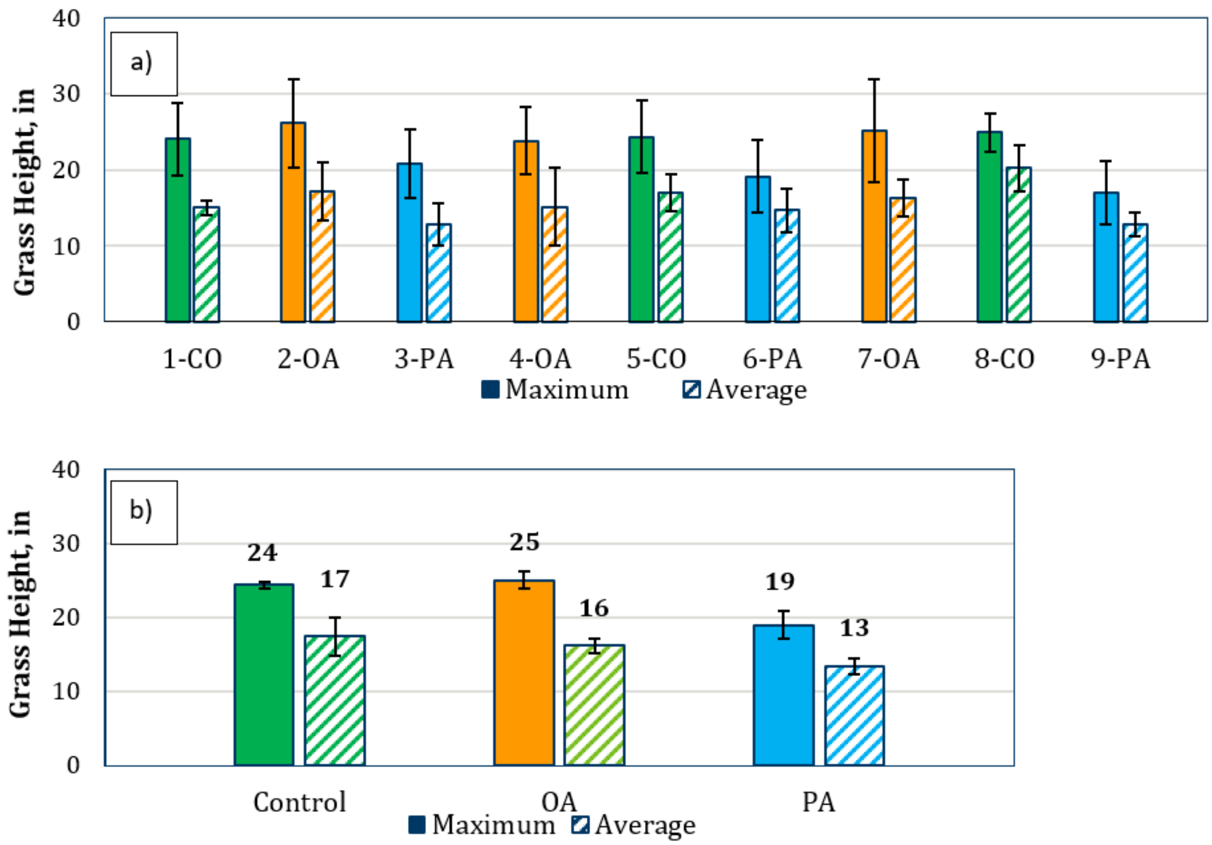


Figure 6.19 (a) Maximum and average grass heights measured for each field plot at the end of 1st Cycle 140 days after seeding, and (b) the average grass heights measured from Control, OA, and PA plots.

Cycle 2 Plant Heights (June 2024): In Cycle 2, the length measurement methodology employed in Cycle 1 was maintained. However, unlike Cycle 1, where height measurements were taken at the cycle's end (October 2023), Cycle 2 measurements were conducted at the beginning of June 2024 365 days after seeding. The height measurements recorded as of the first week of June 2024 are illustrated in Figure 6.20. In Cycle 2, forbs-flowering plant heights in the OA plots reached a maximum of 30±2 inches and averaged 25±3 inches. Conversely, the PA plots exhibited maximum and average heights of 25±1 and 21±1 inches, respectively, while the control plots recorded maximum and average heights of 23±1 and 19±1 inches, respectively. When comparing maximum plant heights, the OA plots demonstrated a 30% increase over the control and an 8% increase over the PA plots. On average, OA plots showed a 32% increase in plant height compared to the control and a 19% increase relative to the PA plots, thereby emerging as the most effective treatment. In comparison, the PA plots, on average, yielded an 11% greater plant height than the control.

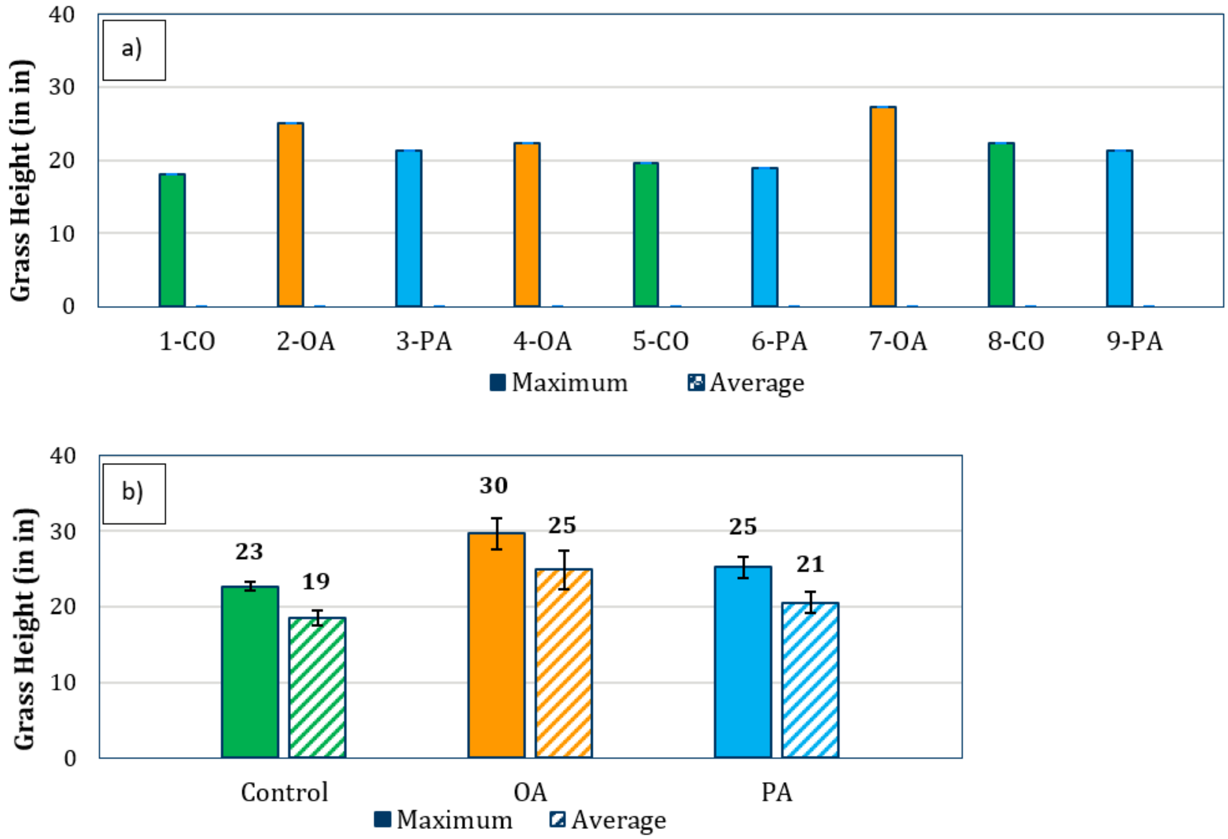


Figure 6.20 (a) Maximum and average grass heights measured for each field plot at the beginning of Cycle 2, 365 days after seeding, and (b) the average grass heights measured from Control, OA and PA plots.

Cycle 2 Plant Heights (October 2024): The final plant heights of forbs-flowering plant in the OA plots reached a peak of 60±5 inches, with an average of 43±2 inches. The PA plots had maximum and average heights of 51±1 and 37±4 inches, respectively, while the control plots recorded maximum and average heights of 46±2 and 35±4 inches. When comparing maximum heights, the OA plots showed a 30% increase over the control and an 17% increase over the PA plots. On average, the OA plots had a 22% higher plant height than the control and a 16% higher height than the PA plots, making OA the most effective treatment. In contrast, the PA plots had an 6% higher average plant height than the control. Figure 6.21 shows the final heights measurements at Cycle 2.

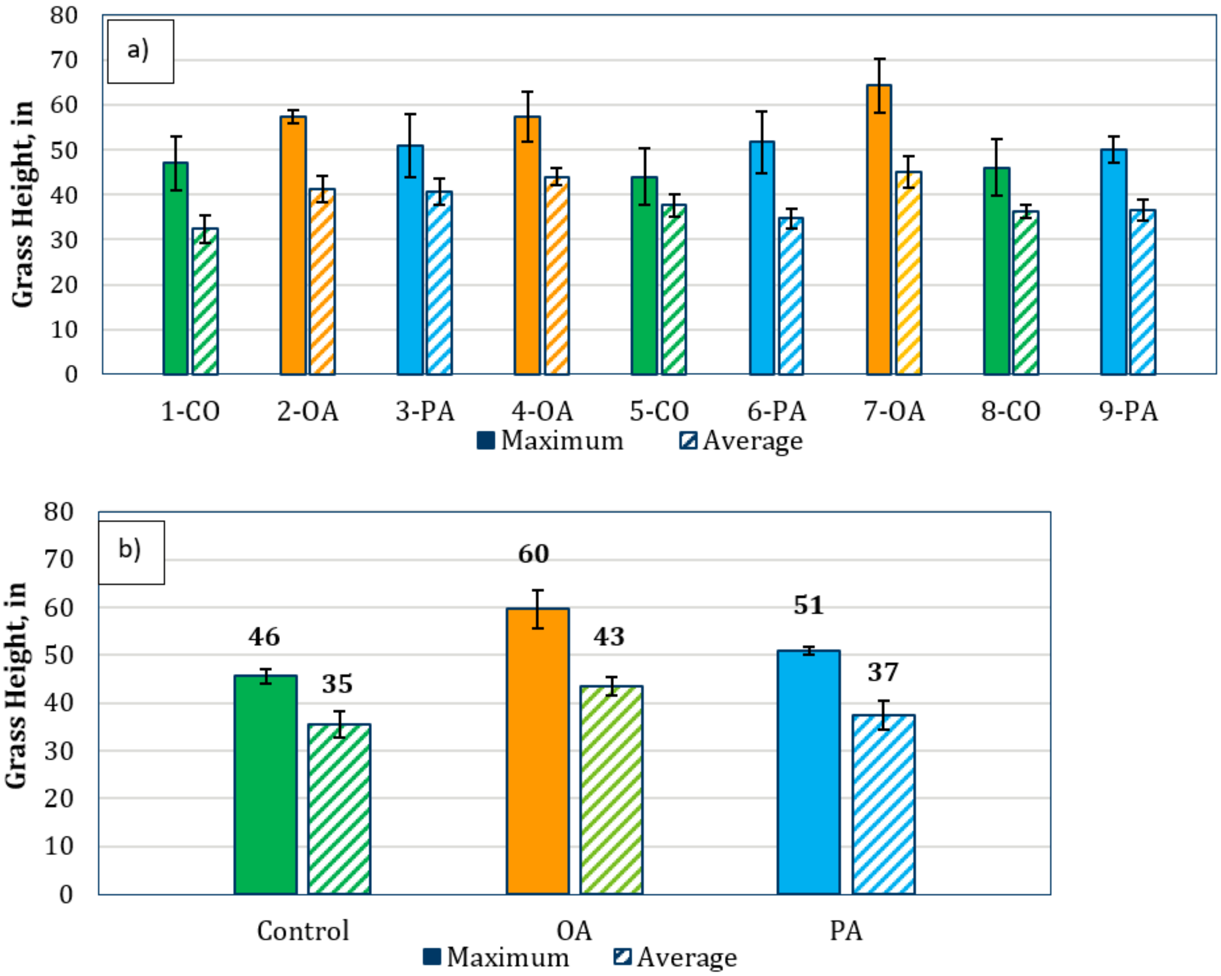


Figure 6.21 (a) Maximum and average grass heights measured for each field plot at the end of Cycle 2, 500 days after seeding, and (b) the average grass heights measured from Control, OA and PA plots.

6.6.2 Water Quality

This section analyzes the data collected for water quality from Cycle 1 and Cycle 2. Traditional constituents (pH, EC, and TSS) and nutrient constituents (TN and TP) are discussed in this section.

6.6.2.1 Traditional Constituents

The pH of the water samples collected from the control, PA and OA plots fluctuated at the beginning of Cycle 1, with a peak of 8.45, 8.34, and 8.47, respectively. At the end of Cycle 1, the pH exhibited the following order: PA > OA > Control, with stable values 6.98, 6.83, and 6.7, respectively. During the Cycle 2, an increase in the pH values was observed in all plots compared to the values at the end of Cycle 1. (Figure 6.22a).

The initial rise in pH is likely due to plant nutrient uptake, particularly nitrate (NO_3^-), which can lead to the release of bicarbonate (HCO_3^-) into the surrounding soil. This process increases soil pH around the roots, making the soil environment more alkaline (Bolan et al.1991). Conversely, the subsequent decrease in pH can be attributed to the presence of acidic leachates. Rainfall and irrigation can leach away basic cations, which contributes to soil acidification. Ultimately, the pH stabilizes at a plateau due to the soil's buffering capacity.

Electrical conductivity (EC) exhibits a variable trend during the initial weeks of Cycle 1, followed by a gradual decline toward the end of the cycle. At the beginning of Cycle 1, water samples from PA soil were higher than the EC of water from OA and control plots. The EC of water from PA soil was 1,065 µS/cm after the first rainfall event in June 2023 and dropped to 91 µS/cm in August 2023. From August to October 2023, all EC values were lower than the values at the beginning of Cycle 1 (Figure 6.22b). At the beginning of Cycle 2, the EC values were similar to those obtained at the end of Cycle 1. However, an increase in EC value was observed in the water from the soil amended with compost, with a peak of 1,276 µS/cm. Variations in growth cycles between grasses (Cycle 1) and forbs (Cycle 2) can lead to differences in nutrient absorption and release throughout the year, which may influence seasonal fluctuations in runoff electrical conductivity (EC). Also, low water flow may cause salt accumulation and concentration effect, resulting in higher EC values.

During the initial rainfall event in Cycle 1, TSS was 225 mg/L for PA, 27 mg/L for control, and 42 mg/L for OA (Figure 6.22c). In the subsequent three rainfall events, it significantly increased, reaching peak values of 2,120 mg/L for PA, 1,303 mg/L for control, and 800 mg/L for OA. Following these peaks, sediment transport rates declined and approached 20 mg/L, 20 mg/L, and 10 mg/L for control, OA, and PA, respectively by the end of Cycle 1. This reduction in sediment transport can be attributed to the increasing vegetation coverage, which intercepts raindrops and reduces their impact on the soil, thereby minimizing soil erosion and sediment transport (Zhang et al. 2014, Zhang et al. 2015, and Rivers et al. 2021). At the beginning of Cycle 2, sediment transport was higher compared to the end of Cycle 1 due to less established vegetation and ongoing growth. Sediment transport values at the start of Cycle 2 were 197 mg/L for PA, 67 mg/L for Control, and 150 mg/L for OA. These values exhibited a downward trend throughout cycle 2, correlating with the progressive increase in vegetation coverage. Studies, including Hansen et al. (2012) and Ding et al. (2022), have documented that the use of compost and fertilizer materials can enhance vegetation establishment, resulting in reduced runoff and sediment loss.

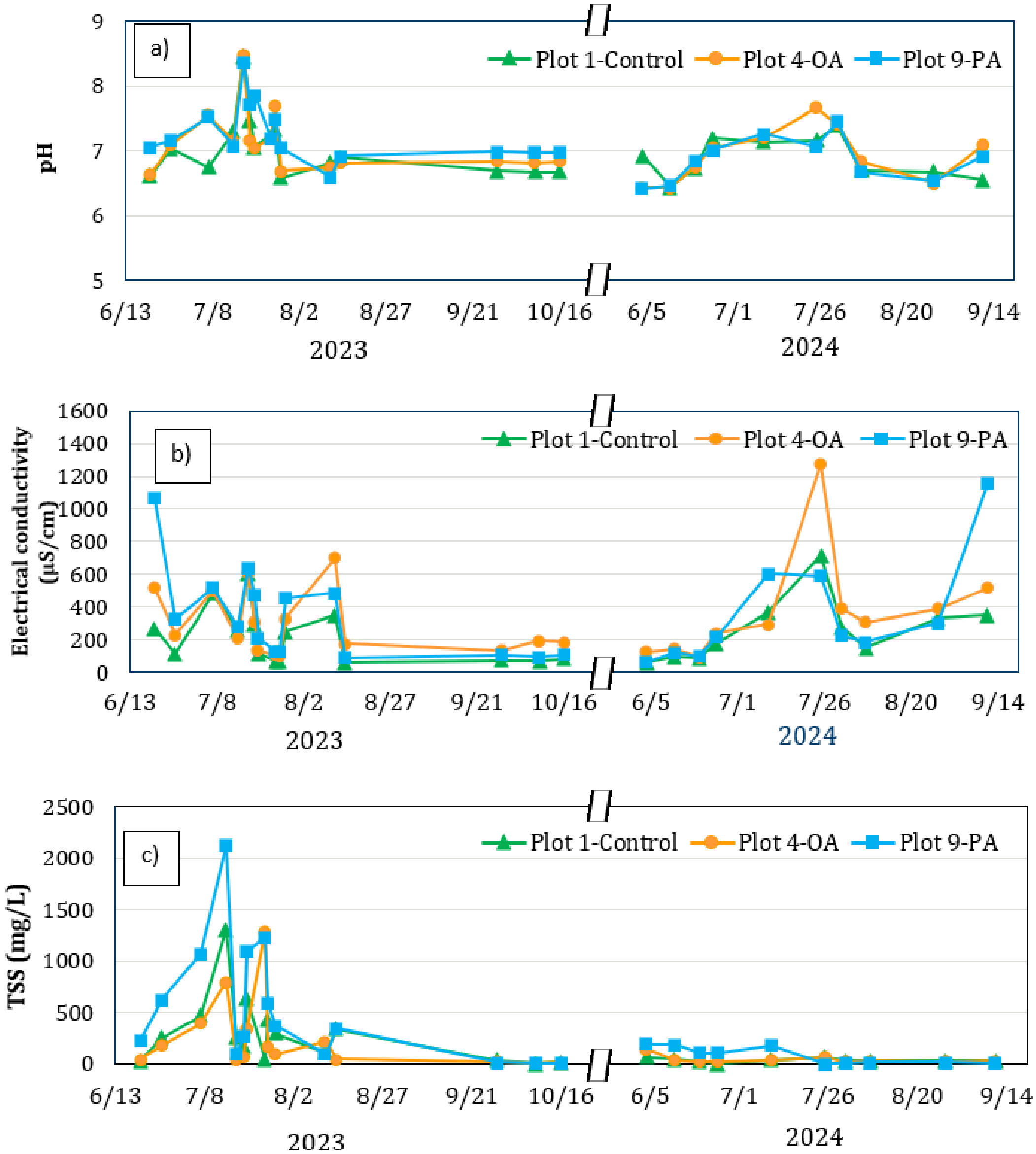


Figure 6.22 (a) Changes in concentrations of pH, (b) electrical conductivity (µS/cm), and (c) total suspended solids (TSS) (mg/L) in soil effluents with time. The timeline between October 2023 and March 2024 indicates the period of dormancy (winter season).

6.6.2.2 Nutrients in runoff

The data on nitrogen and phosphorus from the collected runoff samples are presented in Figure 6.22 and Figure 6.23. All soil samples exhibited a nitrogen release of approximately 30 mg-N/L up until August 2023, maintaining a consistent plateau. Subsequently, nitrogen levels declined significantly, reaching 2.59 mg-N/L in PA, 1.76 mg-N/L in OA, and 1.36 mg-N/L in the control group by the end of Cycle 1. In Cycle 1, up to August 16, data showing a total nitrogen value of 1mg/L were considered below the detection limit for some of the control, OA, and PA samples. The 10 rainfall samples collected during Cycle 2 show a slight upward trend in nitrogen levels compared to values at the end of 1st cycle, although concentrations remained below 10 mg-N/L except for PA on the 26th of September 2024. High TN on this date can be attributed to the presence of some critters in the barrel. Initial concentrations were 13 to 26 times higher than the mean concentrations observed during the steady-state phase at the end of the first cycle. Mukhtar et al. (2009) and Owen et al. (2021) reported similar patterns, with elevated nutrient runoff at the beginning of their studies before declining to lower concentrations.

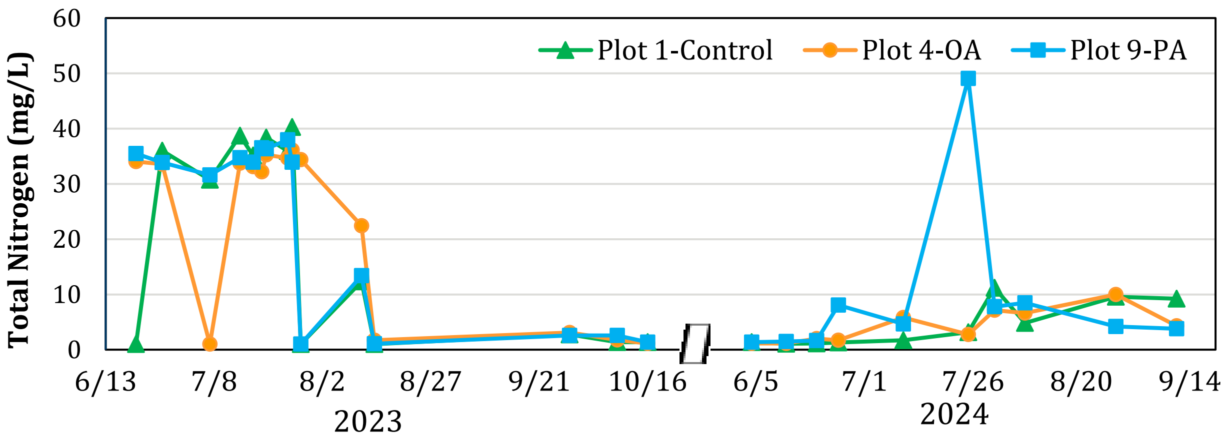


Figure 6.23 Changes in concentrations of TN (in mg/L) in the field with time.

During Cycle 1, the concentration of TP from the water samples of each plot was variable, with peaks of 3.0 mg-P/L and 2.69 mg-P/L from control and compost soil, respectively (Figure 6.24). At the end of Cycle 1, the TP concentration in the water from all plots was lower than 1 mg-P/L. The concentration from the OA plot (0.86 mg-P/L) was higher than PA (0.43 mg-P/L) and control (0.15 mg-P/L). At the beginning of Cycle 2, phosphorus concentrations were consistently below 1 mg/L but increased during July and August 2024 and started to decline until the end of Cycle 2. Over the long term, the control soil and OA soil exhibited a phosphorus concentration of 3.67 mg/L and 4.02 mg/L, respectively by the seventh event of Cycle 2, surpassing levels observed in Cycle 1, when vegetation was absent, and field constructions were newly completed. This indicates that there is a potential for phosphorus release over an extended period for control soil and OA soil.

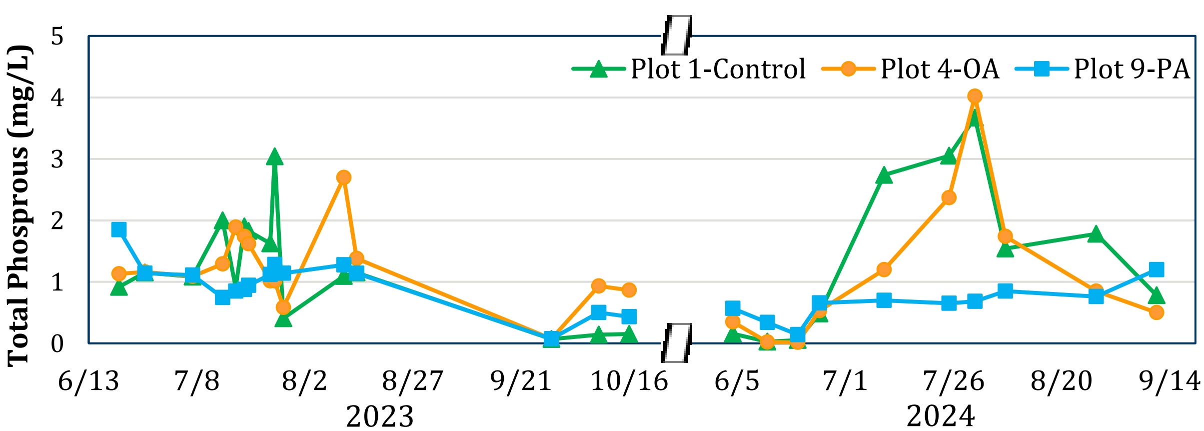
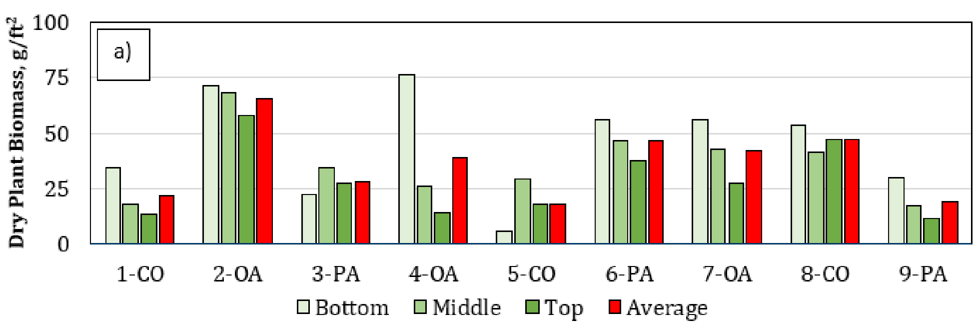


Figure 6.24 Changes in concentrations of TP (in mg/L) in the field with time. The timeline between October 2023 and March 2024 indicates the period of dormancy.

6.6.3 Biomass and Soil Properties

In this section, the data collected for biomass (above-ground and below-ground) and soil property (bulk density) from Cycle 1-140 days after seeding were analyzed.

Above-Ground Biomass (Cycle 1): The dry biomass was collected 140 days after seeding from each plot. In roadside embankments, characterized by their inclined surfaces, variations, and disparities in biomass from the upper to the lower sections were analyzed. The average biomass yield was the highest in OA (49±18 g/ft^2), followed by PA (32±15 g/ft^2) and Control (29±17 g/ft^2). OA soil, treated with yard-waste compost, emerged as the most effective treatment for supporting biomass growth. OA plots increased the above-ground biomass by 69% and 53% compared to Control and PA plots, respectively. PA soil, amended with NPK-rich amendment (Sustane 4-6-4) performed better than unamended control soil, achieving 9% more biomass accumulation. Overall, soil amended with compost (OA) resulted in plant biomass ranging from 31 g/ft^2 to 66 g/ft^2. In contrast, plants cultivated in PA soil exhibited biomass values between 17 g/ft^2 and 47 g/ft^2. For the control soil, plant biomass ranged from 12 g/ft^2 to 46 g/ft^2. It should be noted that biomass accumulation at the bottom of the plot was more pronounced in OA soil, resulting in nearly 100% accumulation at the bottom portion of the slope than at the top portion of the slope. In control soil, the biomass difference between the top and bottom portions was 19%, whereas in PA-amended soil, this difference was up to 44%. This disparity shows that the bottom slope region typically yields higher biomass production compared to the top and middle portions. Figure 6.25 presents the biomass accumulation data, detailing both individual and average values across the field plots.



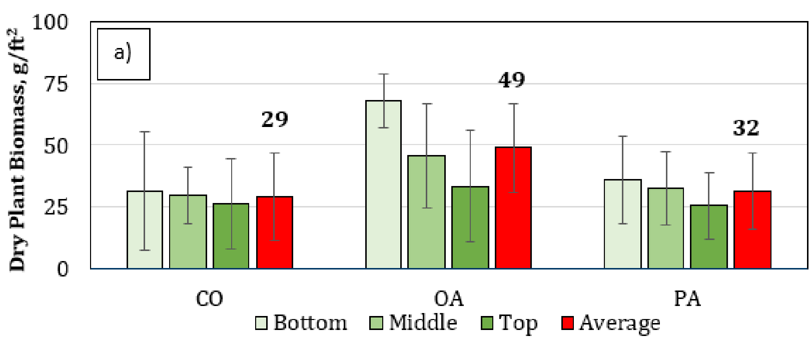
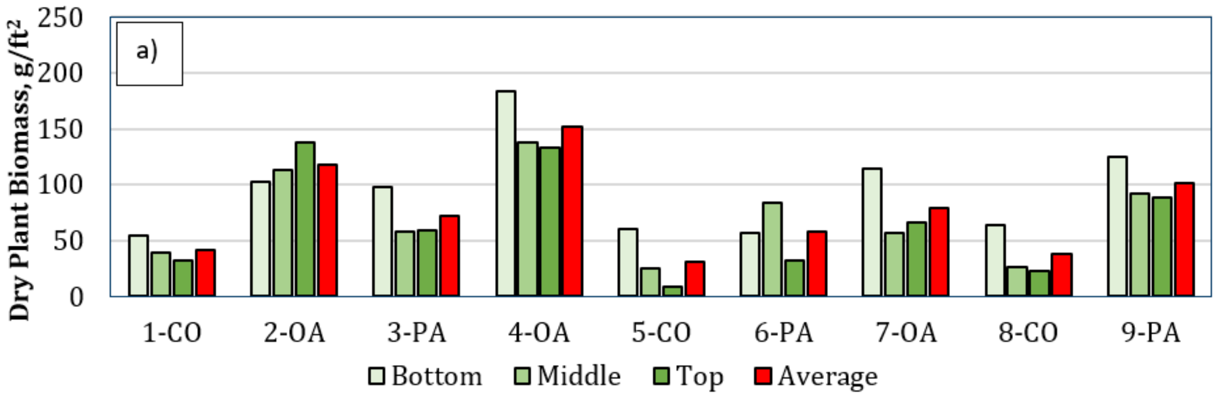


Figure 6.25 (a) Above-ground biomass of each field plot 140 days after seeding, and (b) average of the above-ground biomass of control (CO), organic amendment (OA), and proprietary amendment (PA) plots.

Final Above-Ground Biomass (Cycle 2): The final dry biomass was collected 500 days after seeding from each plot. The highest average total biomass yield was recorded in the OA treatment (117±42 g/ft²), followed by PA (77±27 g/ft²) and the Control (37±8 g/ft²). Soil amended with yard-waste compost (OA) proved to be the most effective in promoting biomass growth. OA plots resulted in a 3 times more above-ground biomass compared to the Control, and a 51% increase compared to the PA plots. Soil treated with the NPK-rich amendment (Sustane 4-6-4) in the PA plots produced nearly 2 times more biomass than the unamended Control soil. Figure 6.26 shows the detailed biomass accumulation data, including both individual and average values for each field plot.



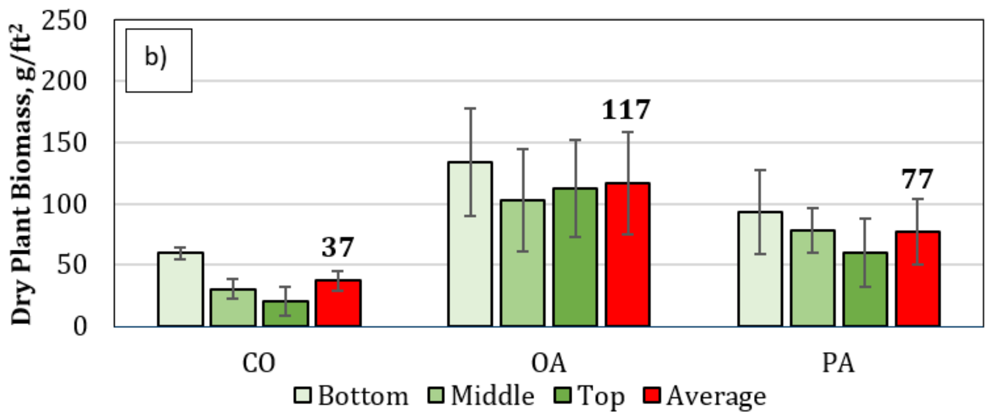


Figure 6.26 (a) Above-ground biomass of each field plot 500 days after seeding, and (b) average of the above-ground biomass of control (CO), organic amendment (OA), and proprietary amendment (PA) plots.

Below-Ground Biomass (Root Density): Among the 54 root samples collected, with 6 samples from the top, medium, and bottom portions of each plot, soil amended with OA demonstrated the highest root density of 0.88±0.31 mg/cm³, whereas PA-amended and control soils had root densities of 0.79±0.23 mg/cm³ and 0.71±0.25 mg/cm³, respectively. OA-amended soil exhibited 11% greater root density compared to PA-amended soil and 23% more than control soil. PA-amended soil showed a 10 percent increase in root density relative to control soil. The root density ranged from 0.35 to 1.15 mg/cm³. Specifically, the total root density of each OA-amended plots (Plots 2,4 and 7) exhibited root densities of 1.14 mg/cm³, 1.15 mg/cm³, and 0.35 mg/cm³ while the total root density of each control plot (Plots 1,5 and 8) showed densities of 0.96 mg/cm³, 0.72 mg/cm³, and 0.46 mg/cm³. The total root density of each PA-amended plot (Plots 3,6 and 9) produced root densities of 1.03

mg/cm³, 0.57 mg/cm³, and 0.76 mg/cm³. Although the OA amendment resulted in the lowest total root density (0.35 mg/cm³) in plot 7 and has some variation (0.88±0.31 mg/cm³) in density values, it seems to be the most effective in terms of root density compared to PA-amended plots and control plots. Additionally, the PA amendment displayed a lower and more consistent range of root densities compared to the control plot. The most pronounced root density difference between the top, medium, and bottom portions was observed in the OA-amended soil because of Plot 4. Figure 6.27 provides a comprehensive overview of root density measurements, showing both individual measurements and the average values across the field plots.

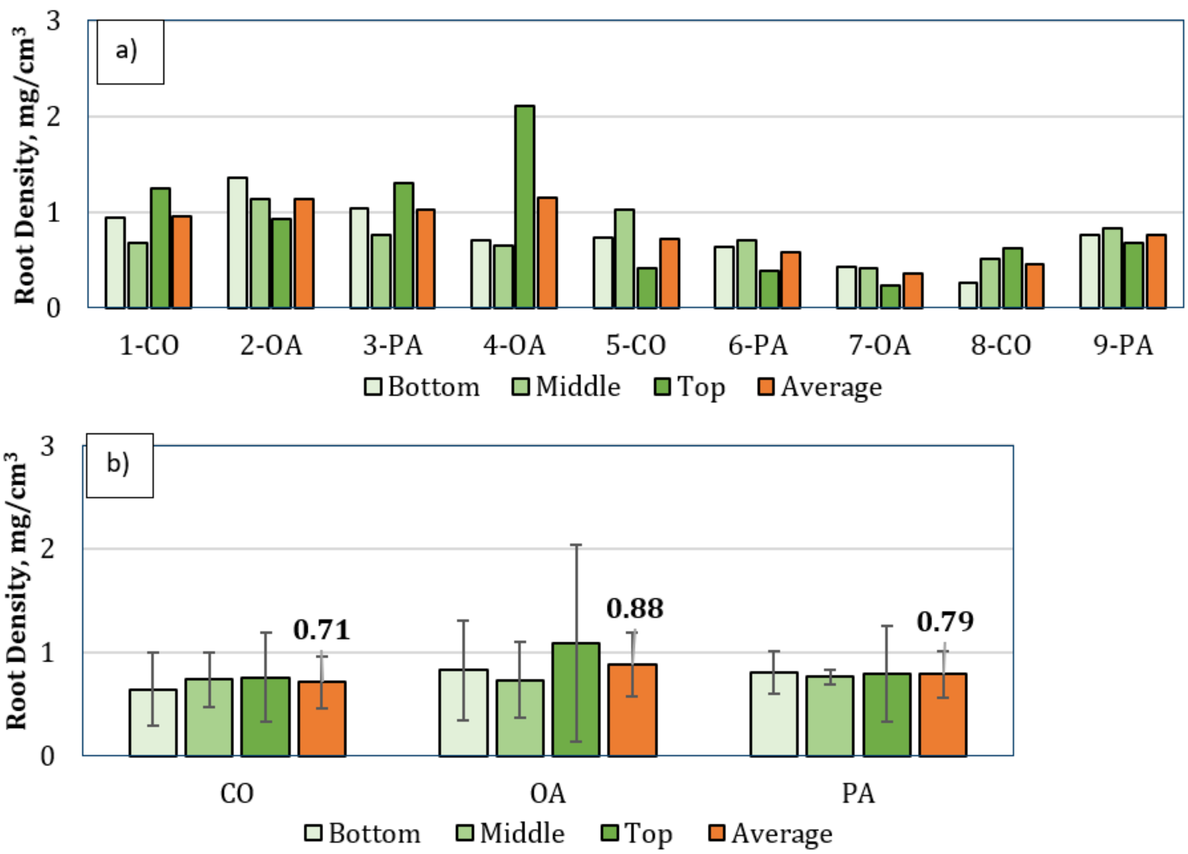


Figure 6.27 (a) Root density of each field plot at the end of 1st Cycle 140 days after seeding, and (b) the average root density of control (CO), organic amendment (OA) and proprietary amendment (PA) plots.

Bulk Density: As a result of bulk density measurements, the bulk density values obtained in the PA and Control plots (1.44±0.10 g/cm^3 and 1.45±0.07 g/cm^3, respectively) were akin to each other; whereas the average bulk density of OA plots was 1.15±0.10 g/cm^3. This indicates that the field application and preparation of plots were consistent across plots. The bulk density of compost was lower and lighter in weight compared to the soil; for this reason, it can lead to a reduced bulk density compared to unamended soil (Agnew and Leonard (2003), Kranz et al. 2021). Figure 6.28 depicts bulk density measurements of field plots.

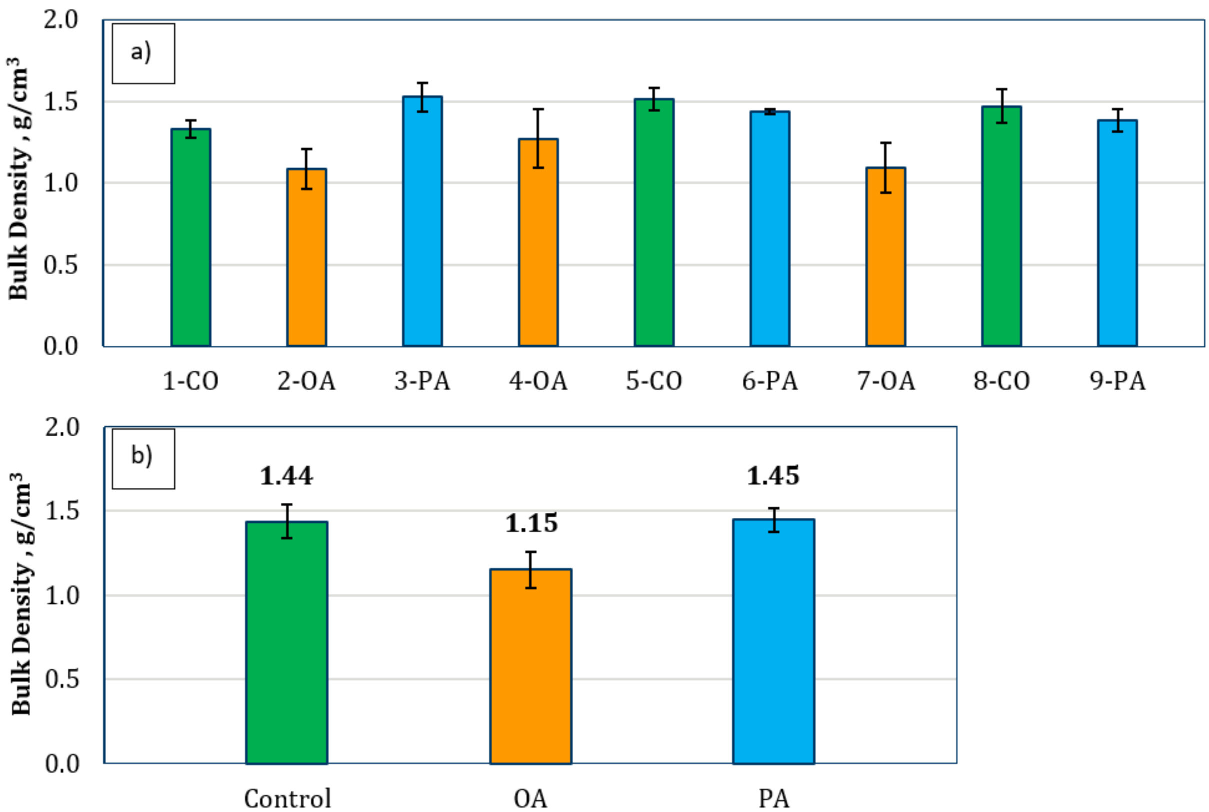


Figure 6.28 (a) Bulk density of soil samples for each field plot at the end of Cycle 1, 140 days after seeding, and (b) the average bulk density of control (CO), organic amendment (OA), and proprietary amendment (PA) plots.

6.7 Chapter Conclusions

Organic amendment yard-waste compost and proprietary soil amendment-Sustane 4-6-4 were used to evaluate their efficiency in promoting more rapid vegetative growth and assess water quality impacts in large-scale field plots mimicking roadside embankments.

OA Influence on Vegetation Growth

1. In terms of above-ground biomass, OA-amended soil emerged as the most effective application, showing a 69±15% and 3 times better performance than unamended control soil in Cycle 1 and Cycle 2, respectively.
2. Regarding below-ground biomass (root density), OA soil improved root density by 23±7% more than control soil.
3. In Cycle 1, OA soil showed nearly the same performance as control soil in terms of maximum and average grass heights; however, OA soil improved the plant heights by 30±2% in Cycle 2.
4. Plant growth across the plots indicated that OA soils yielded earlier growth than unamended control soil. The growth of plants was faster in OA plots.

PA Influence on Vegetation Growth

1. PA plots generated 8±2% and 2 times more above-ground biomass than unamended control plots in Cycle 1 and Cycle 2, respectively.
2. PA soil produced 10±5 % more root density than control plots.
3. During Cycle 1, PA soil stunted the grass height due to a high concentration of weeds but after removing weeds before initiating Cycle 2, it produced 10±1% more maximum and average plant heights.

PA soil outperformed control soil regarding vegetation coverage, leading to faster coverage.

OA Influence on Water Quality

1. Over time, pH levels in OA runoff increased early and plateaued early in Cycle 1 before leveling off to near neutral during the growth period of Cycles 1 and 2.
2. The EC level of OA runoff was lower than PA at the beginning of Cycle 1, but towards the end of the cycle, it reached higher values than the other plots. The second cycle also followed a similar pattern.
3. TSS values from OA-amended plots were significantly lower than PA and control plots, showing less sediment transport.
4. Water quality analysis revealed that the OA-amended soil led to lower N concentration in the runoff water compared to other study soils.
5. OA incorporation caused a higher concentration of phosphorus in the runoff water than in control and PA-amended soils in Cycle 1. In the 2^{nd} cycle, it showed a decreasing trend in the first weeks, then peaked and decreased towards the end of the cycle and OA resulted in a greater concentration of phosphorus compared to PA.

PA Influence on Water Quality

1. Over time, pH levels of water from PA plots increased and reached a plateau after August 2023. pH levels in PA seem more than the control and OA plots in Cycle 1. All soils' pH tended to increase in Cycle 2.
2. EC levels in PA runoff were high at the beginning of Cycle 1 and then, decreased dramatically and followed a steady pattern; however, EC showed an increasing trend in Cycle 2.
3. TSS values were higher in PA waters than in control and OA waters, but they decreased dramatically.
4. Soil amended with PA had a higher concentration of nitrogen than OA and control in both cycles
5. Soil amended with PA had a lower concentration of phosphorus than OA and control in both cycles.

Chapter 7: General Conclusions and Guideline Recommendations

7.1 General Overview

This Minnesota Department of Transportation (MnDOT) project focuses on enhancing vegetation establishment on post-construction roadside embankments by evaluating organic amendments (OAs) and proprietary amendments (PAs) as alternatives to conventional methods like topsoil and fertilizers. Post-construction soils often suffer from compaction, poor fertility, and susceptibility to erosion, causing inadequate stormwater management. This study aims to address these challenges by assessing the performance of compost and proprietary amendments to provide rapid vegetation growth, improve soil quality, and lower construction and maintenance costs. Through comprehensive soil and amendment physicochemical analysis, greenhouse pot experiments, greenhouse mesocosm (large-scale box) experiments, and field experiment, this research evaluates the impact of these amendments on rapid vegetation growth and water quality, aiming to develop practical guidelines and recommendations for effective roadside management practices.

7.2 Amendment Selection Criteria

Selecting the appropriate amendment for a project like roadside vegetation establishment depends on several key factors related to OAs and Pas and the soils to be amended. The selection of the amendments are described below:

Soil Quality

- Nutrient Deficiency: Soil's nutrient deficiencies (e.g., nitrogen, phosphorus, and potassium) should be determined. PAs are appropriate to ameliorate for such deficiencies. Less fertile soil can be improved with organic nutrient-rich compost.
- Soil pH: Amendments should be preferred based on their effect on soil pH. Compost can help buffer soil pH, while some PAs neutralize acidic soils.
- Compaction Levels: If the soil is compacted, incorporating organic amendments such as compost and biochar into compacted soils can enhance porosity, allowing better root penetration and aeration.

Site-Specific Conditions

- Soil Texture: Compost is often preferred for sandy soils requiring higher water retention due to its ability to increase soil moisture. Biochar is also effective for moisture retention. For clayey soils, proprietary amendments might be selected to target soil fertility without further compacting the soil.
- Erosion Potential: For sites prone to erosion, using organic amendments such as compost can stimulate quick vegetation growth, strengthen root systems for soil stability, and reduce soil loss.
- Climate Conditions: If the climate is dry, amendments that improve soil moisture retention, such as biochar or compost, should be prioritized over other alternatives. For colder climates, proprietary

amendments that provide quick nutrient availability might be better to jump-start vegetation establishment.

Target Vegetation

- Native vs. Non-Native Vegetation: Organic amendments are preferred to establish native prairie species because they provide a more balanced nutrient release suitable for native plants. For non-native or turf grass that requires more intensive nutrient support, proprietary amendments can be more appropriate.
- Growth Goals: If rapid establishment is necessary, proprietary amendments are often formulated to provide jump-start, readily available nutrients. Organic amendments are typically more suitable for slower, more growth.

Water Quality Considerations

- Nutrient Leaching Risk: If the release of phosphorus and nitrogen into nearby water bodies is a concern, proprietary amendments have shown reduced nitrogen loss compared to the organic amendments considered in this study. The use of compost might cause the release of phosphorous.

Amendment Properties and Availability

- Nutrient Content: Amendments should be selected based on their nutrient profile. For example, turkey litter compost is rich in nitrogen, while biochar may have limited available nitrogen. In this project, compost soil amendments are chosen not for their nutrient content but for their ability to increase the organic matter in the soil. This increase enhances the soil's organic matter and supports the development of a more robust microbial community, ultimately leading to improved nutrient cycling and reduced fertilization needs. Compost is not intended as a replacement for fertilizer; rather, it is used to increase soil organic matter and deliver the associated long-term benefits.
- Source and Quality: The quality and consistency of compost can vary depending on the feedstock. It's important to assess the amendment's source to ensure it matches the project's requirements. PAs tend to have more consistent quality and nutrient content.
- Local Availability and Cost: Consider logistics such as transportation costs and availability. Organic amendments might be cheaper if sourced locally, but availability may be limited in certain areas and transportation cost of compost might be an issue. PAs, while generally more expensive, are often more readily available of consistent quality.

Environmental Impact and Sustainability

- Organic Matter Content: If the goal is to build organic matter over time, amendments composed of organic materials such as compost would be preferred.

Regulatory Requirements and Guidelines

- Local Regulations: Check local regulations or guidelines regarding the application of amendments. Some areas may have limits on the application rates of certain nutrients or require the use of types of amendments.

Summary of Selection Criteria:

Organic Amendments (OAs): Use compost or biochar to enhance soil structure, increase moisture retention, add organic matter, and promote microbial activity. OAs are beneficial for improving long-term soil health.

Proprietary Amendments (PAs): When rapid vegetation establishment is needed, especially in nutrient-deficient soils, PAs can be selected. PAs are suitable for targeted nutrient application, minimizing nutrient loss.

7.3 Application Methods

To effectively implement soil amendments in roadside projects, starting with an initial assessment of soil properties is crucial. This includes evaluating factors such as texture, nutrient composition, and organic matter content. This initial analysis enables determining appropriate-amendments compost and biochar for site-specific needs. Organic amendments like compost should be incorporated into the topsoil layers to enhance soil structure and support healthy plant growth. Proprietary amendments are particularly effective in providing nutrient support in soils lacking adequate nutrients. Furthermore, ensuring correct incorporation depths is essential to maximize the benefits of amendments while reducing environmental impact. Monitoring critical soil health indicators, like bulk density, organic matter, and nutrient levels, is fundamental for adaptive site management. By using the type of amendment and its application method to the various soil characteristics and slopes, large-scale roadside projects can foster enhancements in vegetation growth, erosion control, and overall soil health, thereby promoting resilience of roadside ecosystems.

7.4 Vegetation Selection and Planting

To ensure effective vegetation establishment for large-scale roadside projects, it is essential to select plant species based on site-specific requirements such as climate adaptability, soil type, and erosion potential is essential. Vegetation must be matched to soil amendments—compost, biochar, or proprietary products—to maximize growth and improve soil health. Combining these strategies can lead to robust and effective roadside environments contributing to erosion control, quick vegetation, and improved aesthetic value.

7.5 Data Collection and Performance Assessment

Measurement of vegetation performance metrics, including biomass, green coverage, and plant height (Chapters 4- Pot Study Report, 5-Mesocosm Study Report, and 6-Field Study Report), is essential for assessing the effectiveness of soil amendments. These metrics offer valuable insights into the vegetative response to different amendment treatments. Visualization methods, such as heatmaps and bar charts, along with statistical tools like ANOVA and MANOVA, are used to compare the effects of amendments across treatments and rank their performance. Figure 7.1 provides the ranking of all amendments and their application rates, evaluated based on individual plant performance metrics across different soil types (Pamuru et al. 2024a). Notably, the MANOVA analysis revealed significant ($p < 0.05$) effects of amendment type on all plant growth metrics, irrespective of soil type.

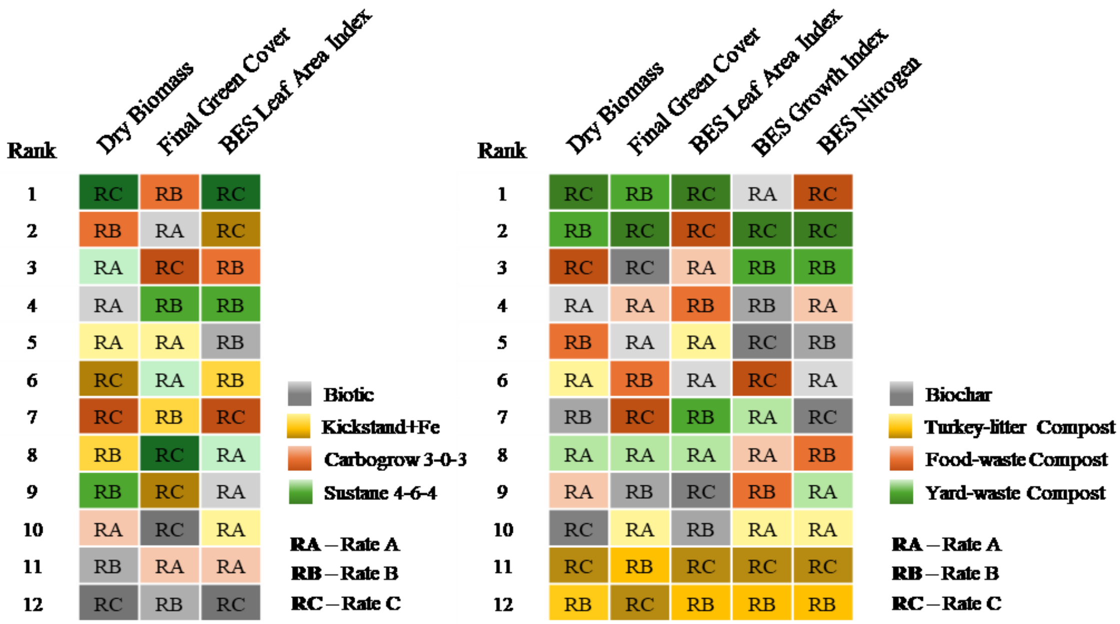


Figure 7.1
Ranking of amendments (a) PAs, and (b) OAs. (Pamuru et al.2024a)

7.6 Growth Assessment: Evaluation of Pot, Mesocosm, and Field Studies

This section presents a comprehensive assessment of vegetation growth across the pot, mesocosm, and field studies, focusing on the effects of organic amendments (OAs) and proprietary amendments (PAs). Key growth metrics evaluated include biomass accumulation, green coverage, root density, leaf area, and growth index.

7.6.1 Organic Amendments (OAs) Influence on Vegetation Growth

OAs evaluated in this study included yard waste (YW), food waste (FW), and turkey litter composts (TL), and a wood-based biochar (B).

Pot Study Findings (OAs tested: YW, FW, TL, B)

- **Coverage, Biomass, and Plant Health:** The TL compost showed limited success, with high soluble salt content and an unfavorable ammonium-to-nitrate ratio causing ammonium toxicity and leading to stunted growth. Faster initial growth was observed in biochar-amended soils, although, plant nitrogen and visual assessments indicated nutrient deficiencies, such as yellowing and crusty edges. The YW and FW composts performed well in terms of producing greater biomass in soil-YW and soil-FW blends. Also, FW contributed to higher nitrogen uptake and leaf area compared to YW. However, greater additions of FW led to delayed growth.

Mesocosm Study Findings (OAs tested: YW, B)

- **Biochar Performance:** Biochar alone stunted growth compared to compost amendments, with lower biomass, leaf area, and coverage.

- **Compost and Compost-Biochar Mixes:** Soils amended with compost alone showed enhanced growth, with compost-biochar mixtures also promoting uniform plant growth. Higher proportions of compost in mixtures resulted in greater plant biomass and leaf area improvements.
- **Uniformity:** Amended soils exhibited more uniform plant coverage than unamended controls, highlighting the effectiveness of OAs in providing consistent growth across the steep soil bed.

Field Study Findings (OAs tested: YW)

- **Biomass and Root Density:** OAs showed significant improvement in vegetation performance, with a 69% increase in above-ground biomass and a 23% improvement in root density compared to unamended control soil 140 days after seeding.
- **Grass Height:** In Cycle 1, OA plots showed grass heights similar to those of the controls. In Cycle 2, plant heights were 30% greater in OA-amended soils, demonstrating an overall enhancement in vegetation growth over 365 days after seeding.
- **Growth Rate:** Early and faster plant growth was observed in OA plots compared to control plots, indicating the ability of OAs to promote rapid establishment of vegetation.

7.6.2 Proprietary Amendments (PAs) Influence on Vegetation Growth

PAs tested included Kickstand, Sustane, Biotic, and Carbogrow.

Pot Study Findings

- **Coverage and Biomass:** The addition of PAs generally led to an increased green coverage across the different soil types. In Ortonville soil, Kickstand and Biotic at rate B significantly improved green coverage, while Sanborn and Glenwood soils saw increases in green coverage with higher rates of Kickstand and Carbogrow.
- **Growth Trends:** Biomass accumulation was highest in Sanborn soil, with Biotic and Carbogrow at A, showing 40-50% increases. Growth index (GI) increased with high rates of Carbogrow in Ortonville soil, demonstrating positive effects on overall plant vigor.

Mesocosm Study Findings

- **Biomass Accumulation:** Sustane at rate B was the most effective amendment for biomass, resulting in a 52% increase compared to control soil. Carbogrow at rate B and Kickstand at rate B also improved biomass, although to a lesser extent.
- **Leaf Area and Coverage:** Sustane at rate B had the most significant impact on leaf area, increasing it 4 times compared to controls. Kickstand and Carbogrow also showed improvements. Green coverage was 57% greater with Sustane at rate B than control soil, and other PAs such as Kickstand at rate B and Carbogrow at rate B also showed higher coverage.
- **Grass Height:** All PAs improved grass height compared to the control, indicating their role in promoting vertical plant growth.

Field Study Findings

- **Biomass and Root Density:** PA plots produced 8% more above-ground biomass and 10% greater root density compared to controls 140 days after seeding.
- **Grass Height:** During Cycle 1, grass height was stunted due to weeds. After weed removal before Cycle 2, PA plots produced 10% greater plant heights than controls 365 days after seeding, highlighting their potential for promoting plant growth when competition is minimized.
- **Vegetation Coverage:** PA-amended soils led to faster vegetation coverage than controls, showing their efficiency in promoting rapid vegetation establishment.

7.6.3 Insights Across Studies

Organic Amendments:

- Effective Biomass Accumulation: Compost amendments, particularly FW and YW, significantly improved above-ground and below-ground biomass compared to unamended soils. Within the selected application rates, increasing soil OM through YW exhibited a linear correlation with growth, whereas FW resulted in delayed growth at higher rates. The increase in biomass (due to the YW amendment) ranged from 69% in field conditions to strong gains in controlled studies.
- Growth Uniformity and Coverage: Compost and compost-biochar mixtures improved growth consistency, while compost alone led to greater plant uniformity across soil beds, with early growth being an important benefit for roadside projects.

Proprietary Amendments:

- **Biomass and Height Increases:** Sustane showed significant success in boosting biomass and leaf area, particularly in the mesocosm study, with gains as high as 52% compared to unamended controls. Similar positive effects were noted in field studies, with increases in root density and above-ground biomass.
- **Rate-Dependent Performance:** Carbogrow and Kickstand demonstrated enhanced growth when applied at manufacturer recommended and higher rates (B and C), emphasizing the importance of optimizing application rates for maximum vegetation growth.
- **Coverage Improvement:** PA amendments resulted in faster vegetation establishment and increased coverage, particularly when weeds were managed, suggesting their usefulness for rapidly establishing protective vegetation cover on disturbed soils.

7.7 Water Quality Assessment: Evaluation Mesocosm and Field Studies

The water quality was evaluated through comprehensive analyses of runoff collected after artificial rainfall events (mesocosm study) and actual rainfall events (field study). Parameters determined include pH, electrical conductivity (EC), total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP). The influence of organic amendments (OAs) and proprietary amendments (PAs) on these water quality parameters was assessed across both large-scale mesocosm and field studies, allowing for an understanding of their impact on environmental runoff quality.

pH Levels: Over time, pH levels in the effluents from all soil treatments (large-scale mesocosm and field study) increased until a steady state. In the mesocosm study, pH levels in both OA and PA amended plots stabilized over time. In the field study, the runoff pH from OA-amended soils showed a similar upward trend, reaching a plateau toward the end of each cycle. The pH levels in the PA-amended plots were generally higher than OA and control soils, particularly toward the end of Cycle 1, suggesting that PA amendments may slightly raise soil pH over time.

Electrical Conductivity (EC): EC levels were used to evaluate the concentration of dissolved ions in the runoff water, which indicates nutrient leaching potential. In the large-scale mesocosm study, EC values decreased over time in both OA and PA treatments, indicating that the release of soluble ions reduced with repeated rainfall. Notably, soil amended with biochar released lower EC values than those treated with compost or compost-biochar, as compost contributes more soluble salts than the biochar used. In the field study, EC levels in OA runoff were initially lower than PA plots during Cycle 1 but exceeded PA levels toward the end of the cycle, showing continued gradual release of soluble salts. PA-amended soils initially had high EC values, which then decreased and stabilized in Cycle 1, followed by an increasing trend in Cycle 2.

Total Suspended Solids (TSS): TSS concentrations in runoff provide an indication of sediment transport and soil erosion. In the large-scale mesocosm study, compost-amended soils had higher TSS in early runoff events, but these values decreased as vegetation cover developed, stabilizing the soil. The biochar-amended soils had relatively lower TSS throughout the study. In the field study, OA plots had significantly lower TSS values than PA and control plots, preventing soil erosion and minimizing sediment transport. PA plots exhibited higher TSS values initially, but these values decreased over time, indicating improvements as the vegetation became established.

Total Nitrogen (TN): Runoff nitrogen was monitored to assess nutrient export and potential leaching risks into water bodies. In the mesocosm study, biochar-amended soil resulted in the lowest nitrogen export, whereas yard-waste compost led to higher nitrogen release. The proprietary amendment Kickstand consistently resulted in lower nitrogen runoff compared to Sustane and Carbogrow. In contrast, the field study OA treatments generally led to lower nitrogen concentrations in runoff compared to PA and control plots. Initially, PA-amended soils consistently had higher nitrogen levels in runoff, likely due to the nutrient-rich composition of these amendments.

Total Phosphorus (TP): Phosphorus runoff was also assessed due to its role in promoting eutrophication. In the mesocosm study, compost-amended soils had higher phosphorus losses, with phosphorus export increasing proportion to compost content. Soils amended with biochar or the proprietary amendments Carbogrow and Sustane effectively retained phosphorus, releasing concentrations lower than the influent values. In the field study, phosphorus concentrations were higher in OA-amended plots than PA and control plots, especially during Cycle 1, indicating that compost additions may increase phosphorus availability and subsequent leaching.

7.7.1 Water Quality Summary

The water quality assessment from both the mesocosm and field studies provides valuable insights into the effects of soil amendments on runoff quality.

1. Runoff pH levels across all treatments generally increased to a stable level, with PA amendments showing slightly higher values; pH should be monitored to ensure it remains within acceptable ranges.
2. EC trends indicate that while both OA and PA amendments initially contribute to elevated ion concentrations, EC values tend to stabilize over time. Biochar appears particularly effective at reducing EC in the runoff.
3. TSS values were notably lower in OA-treated plots compared to PA and control plots, highlighting the effectiveness of organic amendments in preventing erosion and promoting soil stability.
4. Nitrogen and phosphorus concentrations were higher in compost-treated soils, especially during initial phases, emphasizing the need for careful management of compost application rates to avoid nutrient (particularly P) leaching. Proprietary amendments demonstrated better control of nutrient runoff, suggesting their suitability for areas sensitive to nutrient pollution.

7.8 Recommendations for Future Applications and Works

Based on the results from the pot, mesocosm, and field studies, the following recommendations are made:

Organic Amendments:

Across all studies, it is suggested that yard-waste compost be used as the amendment to improve rapid roadside vegetation, reducing runoff volume, and minimizing soil erosion. However, below specific recommendations should be considered:

Pre-Amendment Soil and OA Assessment: It is advised that DOTs evaluate the soil and OA physical (e.g., moisture content, dry bulk density, texture) and chemical properties (e.g., pH, EC, OM, TN, C:N, TP) before incorporating any organic amendments.

Organic Matter Addition: In this study, all Minnesota soils had at least 2% OM; however, an OM range of 4-6% is generally considered optimal for soil fertility. For soils with low OM, incorporating yard-waste compost to boost the OM level by up to 2% is recommended (Table 7.1). For situations requiring an increase beyond 2%, supplementing with biochar is suggested. This approach not only provides additional OM but also enhances soil structure, improves nutrient retention, and promotes vegetation growth when used in combination with compost.

Soil Nutrient Quality Standards: It is further recommended that DOTs establish specific soil nutrient requirements, such as total nitrogen of at least 2000 mg-N/kg and a C:N ratio of 15:1-23:1 in addition to monitoring overall soil organic matter, pH, electrical conductivity, and texture.

Implementing these recommendations can help achieve both vegetation establishment and water quality improvement goals when using OAs.

Proprietary Amendments:

Similar to OA, a pre-assessment of soil quality is recommended before determining the amounts of proprietary amendments required for vegetation establishment. Sustane and Carbogrow (macronutrient-based amendments) show the best potential for enhancing biomass and vegetation coverage. These amendments should be considered where higher nutrient availability and faster growth are required. Moreover, soils with moderate OM content (>3%) can also gain additional nutrient benefits when amended with PAs. Given their potential to improve runoff quality, PAs can be well-suited for areas sensitive to nutrient pollution. Table 7.2 presents the recommended application rates for 1-acre field.

Table 7-1. Yard-waste compost and biochar application rates to achieve a target soil organic matter level for 1-acre field and incorporating into a soil depth of 4-inches. W_{YW} and W_{Bio} correspond to moisture contents of yard-waste compost and biochar respectively.

Amendment	Recommended soil OM increase	Amendment Needed – Dry Wt Basis (ton/acre)	Wet Amendment Needed – Wet Wt Basis (ton/acre)
YW Compost	Up to 2%	Up to ~55	Up to ~ $\left(\frac{55}{1 - W_{YW}}\right)$
YW Compost + Biochar	**YW:** Up to 2% **Biochar:** Up to 2%	**YW:** Up to ~55 **Biochar:** Up to ~25	**YW:** Up to ~ $\left(\frac{25}{1 - W_{YW}}\right)$ **Biochar:** Up to ~ $\left(\frac{25}{1 - W_{Bio}}\right)$

Note: *The application rates are based on the dry weights of yard-waste compost and wood-based biochar used in the mesocosm experiment (Chapter 5). These rates were derived from the percentage of organic amendment added and the corresponding increase in soil OM (see Figure 5.2). Specifically, to increase soil OM by 2%, apply 55 tons/acre of yard-waste compost (containing ~32% OM, Table 4.3) or 25 tons/acre of biochar (containing ~70% OM, Table 4.3), both on a dry-weight basis. Also, prior to estimating the amount of OA to be added, the moisture content (W_{YW} AND W_{Bio}) of the amendments should be determined.*

Table 7-2. Proprietary amendment application rates for 1-acre field

Amendment	Recommended Rate (g/ft^2)	Recommended Amount (lb/acre)	Recommended Amount (ton/acre)
Sustane 4-6-4 at Rate B	22.7	2177	1.1
Sustane 4-6-4 at Rate C	45.4	4354	2.2
Carbogrow 3-0-3 at Rate B	18.1	1741	0.9

Weed Management: Effective weed control is critical for both PA and compost treatments to maximize their benefits; however, field study results showed more pronounced growth improvements in PA plots following weed removal.

For future work, the following recommendations are made:

Application Rates: Conduct additional studies focusing on fine-tuning the application rates of both OAs and PAs (based on nutrient contents) to achieve optimal results for biomass growth and water quality. Special attention should be given to preventing nutrient leaching, particularly phosphorus, from compost-treated soils. In addition, microbial measurements of soil should be included in the evaluation.

Synergistic effect of organic amendments: Evaluate combinations of OAs to determine if synergistic effects exist that could enhance growth performance while minimizing adverse environmental impacts.

Long-Term Monitoring: Future projects should incorporate long-term monitoring to evaluate the persistence of vegetation cover and the amendments' effects on soil and water quality over multiple growth cycles.

Water Quality Considerations: Further research should be conducted to investigate mitigation strategies for nutrient runoff, especially for phosphorus, to align with MnDOT guidelines and to prevent eutrophication.

Chapter 8: Summary Of Research Benefits and Implementation Steps

This section presents the quantitative and qualitative benefits of organic and proprietary soil amendments in enhancing vegetation growth and improving water quality in post-construction roadside applications. It provides an overview of outcomes from field studies, including increased biomass and reduced nutrient runoff, alongside qualitative advantages such as improved stormwater management and soil health restoration. In addition, it shows implementation steps, paving the way for adopting solutions for roadside vegetation enhancement and erosion control.

8.1 Quantitative Benefits

This section summarizes the measurable benefits observed from the application of organic and proprietary amendments in field studies.

8.1.1 Vegetation Growth Enhancements

Field studies demonstrated significant improvements in vegetation performance due to the addition of organic and proprietary amendments. Organic amendments (OAs) increased above-ground biomass and root density compared to unamended controls.Proprietary amendments (PAs) showed an increase in above-ground biomass and an improvement in root density. Compost-treated soils provided consistent vegetation coverage, and Sustane 4-6-4 increased biomass. Both applications showed quick vegetation coverage.

8.1.2 Water Quality Enhancements

Effluent analyses from field and mesocosm studies indicated that organic (yard-waste compost and biochar) and proprietary amendments decreased nitrogen losses. However, yard-waste compost contributed to greater phosphorus losses, while proprietary amendments retained phosphorus better, reducing runoff-associated nutrient leaching. TSS values were consistently lower in OA-treated and PA-soils, indicating reduced sediment transport and erosion.

8.1.3 Cost Evaluation Spreadsheet

A cost evaluation spreadsheet was designed to calculate and manage the costs associated with roadside vegetation applications. Using checkboxes, users can select between different amendments (e.g., compost or proprietary amendments). Based on the selected option, the spreadsheet computes the corresponding total costs for the application, including material, excavation machinery, and labor costs. The spreadsheet helps with cost calculations for roadside vegetation projects, supporting efficient decision-making, budgeting, and comparison of various amendments. The cost evaluation spreadsheet guideline is shown in the Appendix D.

8.2 Qualitative Benefits

The qualitative benefits of this study emphasize the broader environmental, hydrological, and practical impacts of using organic and proprietary amendments to restore soil health, enhance stormwater management, and promote roadside vegetation practices.

8.2.1 Soil Health

Applying organic amendments enhanced soil health by improving organic matter content, stabilizing soil structure, and fostering microbial activity. Organic amendments, particularly composts, can increase soil organic matter, creating a nutrient-rich environment that supports plant growth. Compost amendments can reduce bulk density, which can promote root development. Enhanced soil properties can contribute to the restoration of degraded roadside soils, reducing erosion risks.

8.2.2 Stormwater Management

The amendments can improve stormwater management by increasing infiltration rates, reducing surface runoff, and minimizing sediment transport. Amended plots in the field showed lower sediment transport and reduced flooding risks. By reducing nutrient exports, particularly phosphorus and nitrogen, these amendments can help prevent eutrophication in water bodies.

8.2.3 Applicability

The study demonstrated that soil amendments adapt to various roadside conditions across sandy loams and clayey soils, highlighting their applicability to various soil types and environmental conditions. Organic amendments can effectively stabilize soils on steep slopes (2:1), improve soil fertility, and provide long-term vegetation support. Proprietary amendments offered targeted nutrient release, supporting rapid vegetation establishment. Field trials confirmed the applicability of amendments, showing promising results across various site sizes and slopes (2:1 from the mesocosm study and 3:1 from the field study). The ease of application and the availability of materials can make these amendments a practical and effective solution for large-scale post-construction roadside restorations.

8.3 Implementation Steps

The findings from this study provide recommendations for implementing organic and proprietary amendments to improve vegetation growth, soil quality, and stormwater management on post-construction roadside embankments. By following implementation steps, agencies can adopt cost-effective solutions for roadside vegetation establishment and erosion control.

The following steps outline key actions that agencies can take to adopt the research outcomes effectively:

1) **Site Assessment and Initial Soil Testing**
   Site assessments should be conducted to evaluate soil type, compaction levels, organic matter content, and nutrient deficiencies. Baseline testing of soil physical, chemical, and biological properties, including pH,

electrical conductivity (EC), organic matter (OM), and nutrient composition, should be performed to find amendment requirements.

2) **Amendment Selection**
Amendments should be chosen based on site-specific needs, targeting nutrient deficiencies, soil structure, and texture. Yard-waste compost has been shown to provide balance for improving organic matter and soil structure and Sustane 4-6-4 for balanced nutrient supply and plant growth. Moreover, amendments that may result in excessive phosphorus leaching in sensitive areas should be avoided; proprietary amendments and biochar should be prioritized for water-quality protection.

3) **Application Rates and Methods**
Amendments at recommended rates based on laboratory and field study findings should be applied. For example, compost application rates should target a soil TN of at least 2000 mg-N/kg and a 15:1 to 23:1 C:N ratio for optimal growth. It should be noted that amendments should be applied uniformly into the topsoil layer using blending techniques to ensure even distribution.

4) **Vegetation Establishment and Monitoring**
Vegetation coverage, biomass growth, and root density at regular intervals should be monitored to assess performance and identify potential re-treatments.

5) **Water-quality Monitoring**
Small runoff collection systems to measure nutrient leaching and sediment transport from amended areas can be installed. Runoff pH, total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) levels can be monitored to ensure compliance with water-quality standards.

6) **Long-Term Maintenance**
Maintenance schedules for re-vegetation, irrigation, and soil testing to sustain soil health and vegetation growth over time should be developed. Field staff and contractors should be trained in amendment application, monitoring techniques, and management practices.

7) **Policy and Guideline Integration**
Research findings should be incorporated into agency guidelines and construction specifications to standardize amendment selection, application, and performance monitoring.

8.4 Chapter Conclusions

This chapter demonstrates that using organic amendments (OAs) and proprietary amendments (PAs) effectively improves vegetation growth, enhances soil quality, and increases water retention on post-construction roadside embankments. OAs, such as compost, and PAs, such as Sustane 4-6-4, contribute to vegetation growth, nutrient enhancement, and erosion control. Results from greenhouse and field studies confirm that these amendments significantly improve plant biomass production, root density, and water infiltration capacity, supporting rapid vegetation establishment and long-term soil health.

The findings prove that integrating soil amendments into roadside management practices offers an effective approach to addressing soil degradation and stormwater management challenges. Recommendations developed from this research emphasize recommended application rates, site-specific amendment selection, and effective monitoring strategies to pave the way for successful implementation. Adopting the guidelines proposed in this study can reduce long-term maintenance costs, minimize erosion risks, and enhance environmental performance.

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APPENDIX A

SOIL HEALTH REPORTS

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 Cetincentinbor@msu.edu

Sample ID: VVV1655

Field ID: Sanborn Soil

Date Sampled: 10/18/2021

Tillage: no till

Measured Soil Textural Class: **sandy loam**
Sand: **69%** - Silt: **17%** - Clay: **13%**

Group	Indicator	Value	Rating	Constraints
physical	Predicted Available Water Capacity	**0.18**	**76**	
physical	Surface Hardness	Not rated: No Field Penetrometer Readings Submitted		
physical	Subsurface Hardness	Not rated: No Field Penetrometer Readings Submitted		
physical	Aggregate Stability	**10.8**	**13**	Aeration, Infiltration, Rooting, Crusting, Sealing, Erosion, Runoff
biological	Organic Matter Soil Organic Carbon: 1.72 / Total Carbon: 2.58 / Total Nitrogen: 0.14	**2.4**	**67**	
biological	ACE Soil Protein Index	**4.4**	**19**	Organic Matter Quality, Organic N Storage, N Mineralization
biological	Soil Respiration	**0.6**	**50**	
biological	Active Carbon	**540**	**67**	
chemical	Soil pH	**7.7**	**73**	
chemical	Extractable Phosphorus	**6.5**	**100**	
chemical	Extractable Potassium	**79.2**	**100**	
chemical	Minor Elements Mg: 255.7 / Fe: 0.6 / Mn: 12.3 / Zn: 1.3		**100**	

Overall Quality Score: **67** / High

Measured Soil Health Indicators

The Cornell Soil Health Test measures several indicators of soil physical, biological and chemical health. These are listed on the left side of the report summary, on the first page. The "value" column shows each result as a value, measured in the laboratory or in the field, in units of measure as described in the indicator summaries below. The "rating" column interprets that measured value on a scale of 0 to 100, where higher scores are better. Ratings in red are particularly important to take note of, but any in yellow, particularly those that are close to a rating of 30 are also important in addressing soil health problems.

- **A rating below 20 indicates *Very Low (constraining)* functioning and is color-coded red.** This indicates a problem that is likely limiting yields, crop quality, and long-term sustainability of the agroecosystem. In several cases this indicates risks of environmental loss as well. The "constraint" column provides a short list of soil processes that are not functioning optimally when an indicator rating is red. It is particularly important to take advantage of any opportunities to improve management that will address these constraints.
- **A rating between 20 and 40 indicates *Low* functioning and is color-coded orange.** This indicates that a soil process is functioning somewhat poorly and addressing this should be considered in the field management plan. The Management Suggestions Table at the end of the Soil Health Assessment Report provides linkages to field management practices that are useful in addressing each soil indicator process.
- **A rating between 40 and 60 indicates *Medium* functioning and is color-coded yellow.** This indicates that soil health could be better, and yield and sustainability could decrease over time if this is not addressed. This is especially so if the condition is being caused, or not being alleviated, by current management. Pay attention particularly to those indicators rated in yellow and close to 40.
- **A rating between 60 and 80 indicates *High* functioning and is color-coded light green.** This indicates that this soil process is functioning at a non-limiting level. Field soil management approaches should be maintained at the current intensity or improved.
- **A rating of 80 or greater indicates *Very High* functioning and is color-coded dark green.** Past management has been effective at maintaining soil health. It can be useful to note which particular aspects of management have likely maintained soil health, so that such management can be continued. Note that soil health is often high, when first converting from a permanent sod or forest. In these situations, intensive management quickly damages soil health when it includes intensive tillage, low organic matter inputs, bare soils for significant parts of the year, or excessive traffic, especially during wet times.
- **The Overall Quality Score** at the bottom of the report is an average of all ratings, and provides an indication of the soil's overall health status. However, the important part is to know which particular soil processes are constrained or suboptimal so that these issues can be addressed through appropriate management. Therefore, the ratings for each indicator are more important information.

The indicators measured in the Cornell Soil Health Assessment are important soil properties and characteristics in themselves, but also are representative of key soil processes, necessary for the proper functioning of the soil. The following is a summary of the indicators measured, what each of these indicates about your soil's health status, and what may influence the relevant properties and processes described.

A Management Suggestions Table follows, at the end of the report, with short and long term suggestions for addressing constraints or maintaining a well-functioning system. This table will indicate constraints identified in this assessment for your soil sample by the same yellow and red color coding described above. Please also find further useful information by following the links to relevant publications and web resources that follow this section.

Texture is an inherent property of soil, meaning that it is rarely changed by management. It is thus not a soil health indicator *per se* but is helpful both in interpreting the measured values of indicators (see the Cornell Soil Health Assessment Training Manual), and for deciding on appropriate management strategies that will work for that soil.

Your soil's measured textural class and composition: sandy loam Sand: 69% Silt: 17% Clay: 13%

Predicted Available Water Capacity (AWC) is not a directly measured soil property but is modeled from a suite of measured soil health indicators including the percent sand, silt, clay and organic matter. By using a decision tree approach, the developed Random Forest model can predict the laboratory measured AWC value with no more error than that encountered in the raw laboratory analysis. Details of this modeling effort can be found in our Soil Health Management Series Fact Sheet Number 19-05b.

The Soil Health Lab continues to offer the laboratory measured AWC test as an add-on to the soil health package analyses.

The Predicted AWC value is presented as grams of water per gram of soil. This value is scored against an observed distribution in regional soils with similar texture. A physical soil characteristic, AWC is an indicator of the amount of plant-available water the soil can store, and therefore how crops will fare in droughty conditions. Soils with lower storage capacity will cause greater risk of drought stress. AWC is generally lower when total organic matter and/or aggregation is low. It can be improved by reducing tillage, long-term cover cropping, and adding large amounts of well- decomposed organic matter such as compost. Coarse textured (sandy) soils inherently store less water than finer textured soils, so that managing for relatively high-water storage capacity is particularly important in coarse textured soils. While the textural effect cannot be influenced by management, management decisions can be in part based on an understanding of inherent soil characteristics.

> **Your Predicted Available Water Capacity value** is **0.18 g/g**, corresponding with a score of **76**. This score is in the **High** range, relative to soils with similar texture. **This suggests that this soil process is enhancing overall soil resilience. Soil management should aim at maintaining this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.** Please refer to the management suggestions table at the end of this document.

Aggregate Stability is a measure of how well soil aggregates or crumbs hold together under rainfall or other rapid wetting stresses. Measured by the fraction of dried aggregates that disintegrate under a controlled, simulated rainfall event similar in energy delivery to a hard spring rain, the value is presented as a percent and scored against a distribution observed in regional soils with similar textural characteristics. A physical characteristic of soil, Aggregate Stability is a good indicator of soil biological and physical health. Good aggregate stability helps prevent crusting, runoff, and erosion, and facilitates aeration, infiltration, and water storage, along with improving seed germination and root and microbial health. Aggregate stability is influenced by microbial activity, as aggregates are largely held together by microbial colonies and exudates, and is impacted by management practices, particularly tillage, cover cropping, and fresh organic matter additions.

> **Your measured Aggregate Stability value** is **10.8 %**, corresponding with a score of **13**. This score is in the **Very Low (constraining)** range, relative to soils with similar texture. **Aggregate Stability level should be given a high priority in management decisions based on this assessment, as it is likely to be an important constraint to proper soil functioning and sustainability of management at this time.** Please refer to the management suggestions table at the end of this document.

Organic Matter (OM) is a measure of the carbonaceous material in the soil that is biomass or biomass-derived. Measured by the mass lost on combustion of oven-dried soil, the value is presented as a percent of the total soil mass. This is scored against an observed distribution of OM in regional soils with similar texture. A soil characteristic that measures a physical substance of biological origin, OM is a key or central indicator of the physical, biological, and chemical health of the soil. OM content is an important influence on soil aggregate stabilization, water retention, nutrient cycling, and ion exchange capacity. Soils with low organic matter tend to require higher inputs and be less resilient to drought and extreme rainfall. The retention and accumulation of OM is influenced by management practices such as tillage and cover cropping, as well as by microbial community growth. Intensive tillage and lack of organic matter biomass additions from various sources (amendments, residues, active crop or cover crop growth) will decrease organic matter content and overall soil health with time.

Total Carbon (Tot C) is an indicator for the OM in soil, with carbon comprising 48-58% of the total weight of OM. The Tot C analysis measures all the carbon in a sample using complete oxidation of carbon to CO2 using high temperature combustion (1100C). The measured Tot C includes ***organic*** forms of carbon (Soil Organic Carbon SOC), comprised of available carbon as well as relatively inert carbon in stable organic materials. Carbon can also be found in ***inorganic*** form (Soil Inorganic Carbon SIC) as carbonate minerals such as calcium carbonate (lime).

Soil Organic Carbon (SOC) is equivalent to Tot C when there are no carbonate minerals. However, soils above pH 6.5 may contain high levels of carbonates. These carbonates are measured as SIC and subtracted from the Tot C: **SOC = Tot C - SIC**.

Total Nitrogen (Tot N) includes the organic (living and non-living) and inorganic (or mineral) forms of nitrogen. About half of the Tot N found in soil is in relatively stable organic compounds. Inorganic nitrogen is liberated from organic nitrogen sources in the soil, particularly proteins and amino acids through the action of soil microorganisms. Ammonium (NH4+) and nitrate (NO3-) are the inorganic forms of nitrogen found in soil that are plant available. The Tot N is determined following the combustion methodology known as DUMAS.

Your measured Organic Matter value is **2.4 %**, corresponding with a score of **67**. This score is in the **High** range, relative to soils with similar texture. **This suggests that this soil process is enhancing overall soil resilience. Soil management should aim at maintaining this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.** Please refer to the management suggestions table at the end of this document. The **SOC** level is **1.72%**, the **Tot C** level is **2.58%**, the **Tot N** level is **0.14%**.

Soil Proteins are the fraction of the soil organic matter that are present as proteins or protein-like substances. This represents the large pool of organically bound N in the SOM, which microbial activity can mineralize, and make available for plant uptake. Measured by extraction with a citrate buffer under high temperature and pressure (hence Autoclave Citrate Extractable, or ACE proteins), the value given is expressed in mg extracted per gram of soil. As the method used extracts only a readily extractable fraction of the total amount of soil proteins in the SOM, we present this value as an index rather than as an absolute quantity. A measure of a physical substance, protein content is an indicator of the biological and chemical health of the soil and is very well associated with overall soil health status. Protein content, as organically bound N, influences the ability of the soil to make N available by mineralization, and has been associated with soil aggregation and water movement. Protein content can be influenced by biomass additions, the presence of roots and soil microbes, and tends to decrease with increasing soil disturbance such as tillage.

Your measured ACE Soil Protein Index value is **4.4,** corresponding with a score of **19**. This score is in the **Very Low (constraining)** range, relative to soils with similar texture. **ACE Soil Protein Index level should be given a high priority in management decisions based on this assessment, as it is likely to be an important constraint to proper soil functioning and sustainability of management at this time.** Please refer to the management suggestions table at the end of this document.

Soil Respiration is a measure of the metabolic activity of the soil microbial community. Measured by capturing and quantifying carbon dioxide (CO 2) produced by this activity, the value is expressed as total CO 2 released (in mg) per gram of soil over a 4 day incubation period.

Respiration is scored against an observed distribution in regional soils, taking texture into account. A direct biological activity measurement, respiration is an indicator of the biological status of the soil community, integrating abundance and activity of microbial life. Soil biological activity accomplishes numerous important functions, such as cycling of nutrients into and out of soil OM pools, transformations of N between its several forms, and decomposition of incorporated residues. Soil biological activity influences key physical characteristics like OM accumulation, and aggregate formation and stabilization. Microbial activity is influenced by management practices such as tillage, cover cropping, manure or green manure incorporation, and biocide (pesticide, fungicide, herbicide) use.

Your measured Soil Respiration value is **0.6 mg**, corresponding with a score of **50**. This score is in the **Medium** range, relative to soils with similar texture. **This suggests that, while Soil Respiration is functioning at an average level, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning. Soil management should aim at improving this functionality while addressing any other**

measured soil constraints as identified in the Soil Health Assessment Report. Please refer to the management suggestions table at the end of this document.

Active Carbon is a measure of the small portion of the organic matter that can serve as an easily available food source for soil microbes, thus helping maintain a healthy soil food web. Measured by potassium permanganate oxidation, the value is presented in parts per million (ppm) and scored against an observed distribution in regional soils with similar texture. While a measure of a class of physical substances, active carbon is a good leading indicator of biological soil health and tends to respond to changes in management earlier than total organic matter content, because when a large population of soil microbes is fed plentifully with enough organic matter over an extended period of time, well-decomposed organic matter builds up. A healthy and diverse microbial community is essential to maintain disease resistance, nutrient cycling, aggregation, and many other important functions. Intensive tillage and lack of organic matter additions from various sources (amendments, residues, active crop or cover crop growth) will decrease active carbon, and thus will over the longer term decrease total organic matter.

Your measured Active Carbon value is **540 ppm**, corresponding with a score of **67**. This score is in the **High** range, relative to soils with similar texture. **This suggests that this soil process is enhancing overall soil resilience. Soil management should aim at maintaining this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.** Please refer to the management suggestions table at the end of this document.

Soil pH is a measure of how acidic the soil is, which controls how available nutrients are to crops. A physico-chemical characteristic of soils, pH is an indicator of the chemical or nutrient status of the soil. Measured with an electrode in a 1:1 soil:water suspension, the value is presented in standard pH units, and scored using an optimality curve. Optimum pH is around 6.2-6.8 for most crops (exceptions include potatoes and blueberries, which grow best in more acidic soil – this is not accounted for in the report interpretation). If pH is too high, nutrients such as phosphorus, iron, manganese, copper and boron become unavailable to the crop. If pH is too low, calcium, magnesium, phosphorus, potassium and molybdenum become unavailable. Lack of nutrient availability will limit crop yields and quality. Aluminum toxicity can also be a concern in low pH soils, which can severely decrease root growth and yield, and in some cases lead to accumulation of aluminum and other metals in crop tissue. In general, as soil OM increases, crops can tolerate lower soil pH. Soil pH also influences the ability of certain pathogens to thrive, and of beneficial organisms to effectively colonize roots. Raising the pH through lime or wood ash applications, and organic matter additions, will help immobilize aluminum and heavy metals, and maintain proper nutrient availability.

Your measured Soil pH value is **7.7,** corresponding with a score of **73**. This score is in the **High** range, relative to soils with similar texture. **This suggests that this soil process is enhancing overall soil resilience. Soil management should aim at maintaining this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.** Please refer to the management suggestions table at the end of this document.

Extractable Phosphorus is a measure of phosphorus (P) availability to a crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm), and scored against an optimality curve for sufficiency or excess. P is an essential plant macronutrient, and its availability varies with soil pH and mineral composition. Low P values indicate poor P availability to plants, and excessively high P values indicates a risk of adverse environmental impact through runoff and contamination of surface waters. Most soils in the Northeast store unavailable P from the soil's mineral make up or from previously applied fertilizer or manure. This becomes more available to plants as soils warm up. Therefore, incorporating or banding 10-25 lbs/acre of soluble 'starter' P fertilizer at planting can be useful even when soil levels are optimum. Some cover crops, such as buckwheat, are good at mining otherwise unavailable P so that it becomes more available to the following crop. When plants associate with mycorrhizal fungi, these can also help make P (and other nutrients and water) more available to the crop. P is an environmental contaminant and runoff of P into fresh surface water will cause damage through eutrophication, so over-application is strongly discouraged, especially close to surface water, on slopes, and on large scales.

> **Your measured Extractable Phosphorus value** is **6.5 ppm**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Extractable Potassium is a measure of potassium (K) availability to the crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm) and scored against an optimality curve for sufficiency. K is an indicator of soil nutrient status, as it is an essential plant macronutrient. Plants with higher potassium tend to be more tolerant of frost and cold. Thus, good potassium levels may help with season extension. While soil pH only marginally affects K availability, K is easily leached from sandy soils and is only weakly held by increased organic matter, so that applications of the amount removed by the specific crop being grown are generally necessary in such soils.

> **Your measured Extractable Potassium value** is **79.2 ppm**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Minor Elements, also called secondary (calcium, magnesium and sulfur) and micro (iron, manganese, zinc, copper, boron, molybdenum, etc.) nutrients are essential plant nutrients taken up by plants in smaller quantities than the macro nutrients N, P and K. If any minor elements are deficient, this will decrease yield and crop quality, but toxicities can also occur when concentrations are too high. This assessment's minor elements rating indicates whether four measured micronutrients (magnesium, iron, manganese, and zinc) are deficient or excessive.

Micronutrient availability is strongly influenced by pH and organic matter. Low pH increases the availability of most micronutrients, whereas high pH increases the availability of molybdenum, magnesium and calcium. High OM and microbial activity tend to increase micronutrient availability. Note that this test does not measure all important micronutrients. Consider submitting a sample for a complete micronutrient analysis to find out the levels of the other micronutrients.

Your measured Minor Elements Rating is **100**. This score is in the **Very High** range. Magnesium (255.7 ppm) is sufficient, Iron (0.6 ppm) is sufficient, Manganese (12.3 ppm) is sufficient, Zinc (1.3 ppm) is sufficient. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Overall Quality Score: an overall quality score is computed from the individual indicator scores. This score is further rated as follows: less than 20% is regarded as very low, 20-40% is low, 40-60% is medium, 60-80% is high, and greater than 80% is very high. The highest possible quality score is 100 and the least score is 0, thus it is a relative overall soil health status indicator. However, of greater importance than a single overall metric is identification of constrained or suboptimally functioning soil processes, so that these issues can be addressed through appropriate management. The overall soil quality score should be taken as a general summary rather than the main focus.

Your Overall Quality Score is **67**, which is in the **High** range.

Management Suggestions for Physical and Biological Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Predicted Available Water Capacity Low	• Add stable organic materials, mulch • Add compost or biochar • Incorporate high biomass cover crop	• Reduce tillage • Rotate with sod crops • Incorporate high biomass cover crop
Aggregate Stability Low	• Incorporate fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage • Use a surface mulch • Rotate with sod crops and mycorrhizal hosts
Organic Matter Low	• Add stable organic materials, mulch • Add compost and biochar • Incorporate high biomass cover crop	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Incorporate high biomass cover crop
ACE Soil Protein Index Low	• Add N-rich organic matter (low C:N source like manure, high N well-finished compost) • Incorporate young, green, cover crop biomass • Plant legumes and grass-legume mixtures • Inoculate legume seed with Rhizobia & check for nodulation	• Reduce tillage • Rotate with forage legume sod crop • Cover crop and add fresh manure • Keep pH at 6.2-6.5 (helps N fixation) • Monitor C:N ratio of inputs
Soil Respiration Low	• Maintain plant cover throughout season • Add fresh organic materials • Add manure, green manure • Consider reducing biocide usage	• Reduce tillage/mechanical cultivation • Increase rotational diversity • Maintain plant cover throughout season • Cover crop with symbiotic host plants
Active Carbon Low	• Add fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Cover crop whenever possible

Management Suggestions for Chemical Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Soil pH Low	• Add lime or wood ash per soil test recommendations • Add calcium sulfate (gypsum) in addition to lime if aluminum is high • Use less ammonium or urea	• Test soil annually & add "maintenance" lime per soil test recommendations to keep pH in range • Raise organic matter to improve buffering capacity
Soil pH High	• • Stop adding lime or wood ash • Add elemental sulfur per soil test recommendations	• Test soil annually • Use higher % ammonium or urea
Extractable Phosphorus Low	• Add P amendments per soil test recommendations • Use cover crops to recycle fixed P • Adjust pH to 6.2-6.5 to free up fixed P	• Promote mycorrhizal populations • Maintain a pH of 6.2-6.5 • Use cover crops to recycle fixed P
Extractable Phosphorus High	• Stop adding manure and compost • Choose low or no-P fertilizer blend • Apply only 20 lbs/ac starter P if needed • Apply P at or below crop removal rates	• Use cover crops that accumulate P and export to low P fields or offsite • Consider low P rations for livestock • Consider phytase for non-ruminants
Extractable Potassium Low	• Add wood ash, fertilizer, manure, or compost per soil test recommendations • Use cover crops to recycle K • Choose a high K fertilizer blend	• Use cover crops to recycle K • Add "maintenance" K per soil recommendations each year to keep K consistently available
Minor Elements Low	• Add chelated micros per soil test recommendations • Use cover crops to recycle micronutrients • Do not exceed pH 6.5 for most crops	• Promote mycorrhizal populations • Improve organic matter • Decrease soil P (binds micros)
Minor Elements High	• Raise pH to 6.2-6.5 (for all high micros except Molybdenum) ▪ Do not use fertilizers with micronutrients •	○ Maintain a pH of 6.2-6.5 ○ Monitor irrigation/improve drainage • Improve soil calcium levels

School of Integrative Plant Science, Soil and Crop Sciences Section, G01 Bradfield Hall, 306 Tower Road, Cornell University, Ithaca, NY 14853, email: soilhealth@cornell.edu

College of Agriculture and Life Sciences, Cornell University Developed in partnership with Cornell Soil Health, Farmier, and GreenStart.

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.

Grower: Bora Cetin centinbor@msu.edu		Sample ID:	VVV1656
		Field ID:	Glenwood Soil
		Date Sampled:	11/04/2021
		Tillage:	no till

Measured Soil Textural Class: **sandy loam** Sand: **65%** - Silt: **18%** - Clay: **15%**

Group	Indicator	Value	Rating	Constraints
physical	Predicted Available Water Capacity	**0.20**	**83**	
physical	Surface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Subsurface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Aggregate Stability	**17.5**	**22**	
biological	Organic Matter Soil Organic Carbon: 1.84 / Total Carbon: 2.17 / Total Nitrogen: 0.15	**3.6**	**97**	
biological	ACE Soil Protein Index	**4.6**	**20**	
biological	Soil Respiration	**0.5**	**39**	
biological	Active Carbon	**536**	**66**	
chemical	Soil pH	**7.5**	**93**	
chemical	Extractable Phosphorus	**1.7**	**49**	
chemical	Extractable Potassium	**61.0**	**86**	
chemical	Minor Elements Mg: 410.7 / Fe: 0.4 / Mn: 8.4 / Zn: 0.2		**56**	

Overall Quality Score: **61** / High

Measured Soil Health Indicators

The Cornell Soil Health Test measures several indicators of soil physical, biological and chemical health. These are listed on the left side of the report summary, on the first page. The "value" column shows each result as a value, measured in the laboratory or in the field, in units of measure as described in the indicator summaries below. The "rating" column interprets that measured value on a scale of 0 to 100, where higher scores are better. Ratings in red are particularly important to take note of, but any in yellow, particularly those that are close to a rating of 30 are also important in addressing soil health problems.

- **A rating below 20 indicates *Very Low (constraining)* functioning and is color-coded red.** This indicates a problem that is likely limiting yields, crop quality, and long-term sustainability of the agroecosystem. In several cases this indicates risks of environmental loss as well. The "constraint" column provides a short list of soil processes that are not functioning optimally when an indicator rating is red. It is particularly important to take advantage of any opportunities to improve management that will address these constraints.

- **A rating between 20 and 40 indicates *Low* functioning and is color-coded orange.** This indicates that a soil process is functioning somewhat poorly and addressing this should be considered in the field management plan. The Management Suggestions Table at the end of the Soil Health Assessment Report provides linkages to field management practices that are useful in addressing each soil indicator process.

- **A rating between 40 and 60 indicates *Medium* functioning and is color-coded yellow.** This indicates that soil health could be better, and yield and sustainability could decrease over time if this is not addressed. This is especially so if the condition is being caused, or not being alleviated, by current management. Pay attention particularly to those indicators rated in yellow and close to 40.
- **A rating between 60 and 80 indicates *High* functioning and is color-coded light green.** This indicates that this soil process is functioning at a non-limiting level. Field soil management approaches should be maintained at the current intensity or improved.

- **A rating of 80 or greater indicates *Very High* functioning and is color-coded dark green.** Past management has been effective at maintaining soil health. It can be useful to note which particular aspects of management have likely maintained soil health, so that such management can be continued. Note that soil health is often high, when first converting from a permanent sod or forest. In these situations, intensive management quickly damages soil health when it includes intensive tillage, low organic matter inputs, bare soils for significant parts of the year, or excessive traffic, especially during wet times.

The Overall Quality Score at the bottom of the report is an average of all ratings and provides an indication of the soil's overall health status. However, the important part is to know which particular soil processes are constrained or suboptimal so that these issues can be addressed through appropriate management. Therefore the ratings for each indicator are more important information.

The indicators measured in the Cornell Soil Health Assessment are important soil properties and characteristics in themselves, but also are representative of key soil processes, necessary for the proper functioning of the soil. The following is a summary of the indicators measured, what each of these indicates about your soil's health status, and what may influence the relevant properties and processes described.

A Management Suggestions Table follows, at the end of the report, with short- and long-term suggestions for addressing constraints or maintaining a well-functioning system. This table will indicate constraints identified in this assessment for your soil sample by the same yellow and red color coding described above. Please also find further useful information by following the links to relevant publications and web resources that follow this section.

Texture is an inherent property of soil, meaning that it is rarely changed by management. It is thus not a soil health indicator *per se* but is helpful both in interpreting the measured values of indicators (see the Cornell Soil Health Assessment Training Manual), and for deciding on appropriate management strategies that will work for that soil.

Your soil's measured textural class and composition: sandy loam Sand: 65% Silt: 18% Clay: 15%

Predicted Available Water Capacity (AWC) is not a directly measured soil property but is modeled from a suite of measured soil health indicators including the percent sand, silt, clay and organic matter. By using a decision tree approach, the developed Random Forest model can predict the laboratory measured AWC value with no more error than that encountered in the raw laboratory analysis. Details of this modeling effort can be found in our Soil Health Management Series Fact Sheet Number 19-05b.

The Soil Health Lab continues to offer the laboratory measured AWC test as an add-on to the soil health package analyses.

The Predicted AWC value is presented as grams of water per gram of soil. This value is scored against an observed distribution in regional soils with similar texture. A physical soil characteristic, AWC is an indicator of the amount of plant-available water the soil can store, and therefore how crops will fare in droughty conditions. Soils with lower storage capacity will cause greater risk of drought stress. AWC is generally lower when total organic matter and/or aggregation is low. It can be improved by reducing tillage, long-term cover cropping, and adding large amounts of well-decomposed organic matter such as compost. Coarse textured (sandy) soils inherently store less water than finer textured soils, so that managing for relatively high-water storage capacity is particularly important in coarse textured soils. While the textural effect cannot be influenced by management, management decisions can be in part based on an understanding of inherent soil characteristics.

> **Your Predicted Available Water Capacity value** is **0.20 g/g**, corresponding with a score of **83**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Aggregate Stability is a measure of how well soil aggregates or crumbs hold together under rainfall or other rapid wetting stresses. Measured by the fraction of dried aggregates that disintegrate under a controlled, simulated rainfall event similar in energy delivery to a hard spring rain, the value is presented as a percent and scored against a distribution observed in regional soils with similar textural characteristics. A physical characteristic of soil, Aggregate Stability is a good indicator of soil biological and physical health. Good aggregate stability helps prevent crusting, runoff, and erosion, and facilitates aeration, infiltration, and water storage, along with improving seed germination and root and microbial health. Aggregate stability is influenced by microbial activity, as aggregates are largely held together by microbial colonies and exudates, and is impacted by management practices, particularly tillage, cover cropping, and fresh organic matter additions.

> **Your measured Aggregate Stability value** is **17.5 %**, corresponding with a score of **22**. This score is in the **Low** range, relative to soils with similar texture. **This suggests that, while Aggregate Stability does not currently register as a strong constraint, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning.** Please refer to the management suggestions table at the end of this document.

Organic Matter (OM) is a measure of the carbonaceous material in the soil that is biomass or biomass-derived. Measured by the mass lost on combustion of oven-dried soil, the value is presented as a percent of the total soil mass. This is scored against an observed distribution of OM in regional soils with similar texture. A soil characteristic that measures a physical substance of biological origin, OM is a key or central indicator of the physical, biological, and chemical health of the soil. OM content is an important influence on soil aggregate stabilization, water retention, nutrient cycling, and ion exchange capacity. Soils with low organic matter tend to require higher inputs and be less resilient to drought and extreme rainfall. The retention and accumulation of OM is influenced by management practices such as tillage and cover cropping, as well as by microbial community growth. Intensive tillage and lack of organic matter biomass additions from various sources (amendments, residues, active crop or cover crop growth) will decrease organic matter content and overall soil health with time.

Total Carbon (Tot C) is an indicator for the OM in soil, with carbon comprising 48-58% of the total weight of OM. The Tot C analysis measures all of the carbon in a sample using complete oxidation of carbon to CO2 using high temperature combustion (1100C). The measured Tot C includes ***organic*** forms of carbon (Soil Organic Carbon SOC), comprised of available carbon as well as relatively inert carbon in stable organic materials. Carbon can also be found in ***inorganic*** form (Soil Inorganic Carbon SIC) as carbonate minerals such as calcium carbonate (lime).

Soil Organic Carbon (SOC) is equivalent to Tot C when there are no carbonate minerals. However, soils above pH 6.5 may contain high levels of carbonates. These carbonates are measured as SIC and subtracted from the Tot C: **SOC = Tot C - SIC**.

Total Nitrogen (Tot N) includes the organic (living and non-living) and inorganic (or mineral) forms of nitrogen. About half of the Tot N found in soil is in relatively stable organic compounds. Inorganic nitrogen is liberated from organic nitrogen sources in the soil, particularly proteins and amino acids through the action of soil microorganisms. Ammonium (NH_4^+) and nitrate (NO_3^-) are the inorganic forms of nitrogen found in soil that are plant available. The Tot N is determined following the combustion methodology known as DUMAS.

> **Your measured Organic Matter value** is **3.6 %**, corresponding with a score of **97**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document. The **SOC** level is **1.84%**, the **Tot C** level is **2.17%**, the **Tot N** level is **0.15%**.

Soil Proteins are the fraction of the soil organic matter that are present as proteins or protein-like substances. This represents the large pool of organically bound N in the SOM, which microbial activity can mineralize, and make available for plant uptake. Measured by extraction with a citrate buffer under high temperature and pressure (hence Autoclave Citrate Extractable, or ACE proteins), the value given is expressed in mg extracted per gram of soil. As the method used extracts only a readily extractable fraction of the total amount of soil proteins in the SOM, we present this value as an index rather than as an absolute quantity. A measure of a physical substance, protein content is an indicator of the biological and chemical health of the soil, and is very well associated with overall soil health status. Protein content, as organically bound N, influences the ability of the soil to make N available by mineralization, and has been associated with soil aggregation and water movement. Protein content can be influenced by biomass additions, the presence of roots and soil microbes, and tends to decrease with increasing soil disturbance such as tillage.

> **Your measured ACE Soil Protein Index value** is **4.6,** corresponding with a score of **20**. This score is in the **Low** range, relative to soils with similar texture. **This suggests that, while ACE Soil Protein Index does not currently register as a strong constraint, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning.** Please refer to the management suggestions table at the end of this document.

Soil Respiration is a measure of the metabolic activity of the soil microbial community. Measured by capturing and quantifying carbon dioxide (CO 2) produced by this activity, the value is expressed as total CO 2 released (in mg) per gram of soil over a 4-day incubation period.

Respiration is scored against an observed distribution in regional soils, taking texture into account. A direct biological activity measurement, respiration is an indicator of the biological status of the soil community, integrating abundance and activity of microbial life. Soil biological activity accomplishes numerous important functions, such as cycling of nutrients into and out of soil OM pools, transformations of N between its several forms, and decomposition of incorporated residues. Soil biological activity influences key physical characteristics like OM accumulation, and aggregate formation and stabilization. Microbial activity is influenced by management practices such as tillage, cover cropping, manure or green manure incorporation, and biocide (pesticide, fungicide, herbicide) use.

Your measured Soil Respiration value is **0.5 mg**, corresponding with a score of **39**. This score is in the **Low** range, relative to soils with similar texture. **This suggests that, while Soil Respiration does not currently register as a strong constraint, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning.** Please refer to the management suggestions table at the end of this document.

Active Carbon is a measure of the small portion of the organic matter that can serve as an easily available food source for soil microbes, thus helping maintain a healthy soil food web. Measured by potassium permanganate oxidation, the value is presented in parts per million (ppm), and scored against an observed distribution in regional soils with similar texture. While a measure of a class of physical substances, active carbon is a good leading indicator of biological soil health and tends to respond to changes in management earlier than total organic matter content, because when a large population of soil microbes is fed plentifully with enough organic matter over an extended period of time, well-decomposed organic matter builds up. A healthy and diverse microbial community is essential to maintain disease resistance, nutrient cycling, aggregation, and many other important functions. Intensive tillage and lack of organic matter additions from various sources (amendments, residues, active crop or cover crop growth) will decrease active carbon, and thus will over the longer term decrease total organic matter.

Your measured Active Carbon value is **536 ppm**, corresponding with a score of **66**. This score is in the **High** range, relative to soils with similar texture. **This suggests that this soil process is enhancing overall soil resilience. Soil management should aim at maintaining this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.** Please refer to the management suggestions table at the end of this document.

Soil pH is a measure of how acidic the soil is, which controls how available nutrients are to crops. A physico-chemical characteristic of soils, pH is an indicator of the chemical or nutrient status of the soil. Measured with an electrode in a 1:1 soil: water suspension, the value is presented in standard pH units and scored using an optimality curve. Optimum pH is around 6.2-6.8 for most crops (exceptions include potatoes and blueberries, which grow best in more acidic soil – this is not accounted for in the report interpretation). If pH is too high, nutrients such as phosphorus, iron, manganese, copper and boron become unavailable to the crop. If pH is too low, calcium, magnesium, phosphorus, potassium and molybdenum become unavailable. Lack of nutrient availability will limit crop yields and quality. Aluminum toxicity can also be a concern in low pH soils, which can severely decrease root growth and yield, and in some cases lead to accumulation of aluminum and other metals in crop tissue. In general, as soil OM increases, crops can tolerate lower soil pH. Soil pH also influences the ability of certain pathogens to thrive, and of beneficial organisms to effectively colonize roots. Raising the pH through lime or wood ash applications, and organic matter additions, will help immobilize aluminum and heavy metals, and maintain proper nutrient availability.

Your measured Soil pH value is **7.5** , corresponding with a score of **93**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management**

practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning. Please refer to the management suggestions table at the end of this document.

Extractable Phosphorus is a measure of phosphorus (P) availability to a crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm), and scored against an optimality curve for sufficiency or excess. P is an essential plant macronutrient, and its availability varies with soil pH and mineral composition. Low P values indicate poor P availability to plants, and excessively high P values indicates a risk of adverse environmental impact through runoff and contamination of surface waters. Most soils in the Northeast store unavailable P from the soil's mineral make up or from previously applied fertilizer or manure. This becomes more available to plants as soils warm up. Therefore, incorporating or banding 10-25 lbs/acre of soluble 'starter' P fertilizer at planting can be useful even when soil levels are optimum. Some cover crops, such as buckwheat, are good at mining otherwise unavailable P so that it becomes more available to the following crop. When plants associate with mycorrhizal fungi, these can also help make P (and other nutrients and water) more available to the crop. P is an environmental contaminant and runoff of P into fresh surface water will cause damage through eutrophication, so over-application is strongly discouraged, especially close to surface water, on slopes, and on large scales.

Your measured Extractable Phosphorus value is **1.7 ppm**, corresponding with a score of **49**. This score is in the **Medium** range, relative to soils with similar texture. **This suggests that, while Extractable Phosphorus is functioning at an average level, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning. Soil management should aim at improving this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.** Please refer to the management suggestions table at the end of this document.

Extractable Potassium is a measure of potassium (K) availability to the crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm), and scored against an optimality curve for sufficiency. K is an indicator of soil nutrient status, as it is an essential plant macronutrient. Plants with higher potassium tend to be more tolerant of frost and cold. Thus, good potassium levels may help with season extension. While soil pH only marginally affects K availability, K is easily leached from sandy soils and is only weakly held by increased organic matter, so that applications of the amount removed by the specific crop being grown are generally necessary in such soils.

Your measured Extractable Potassium value is **61.0 ppm**, corresponding with a score of **86**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Minor Elements, also called secondary (calcium, magnesium and sulfur) and micro (iron, manganese, zinc, copper, boron, molybdenum, etc.) nutrients are essential plant nutrients taken up by plants in smaller quantities than the macro nutrients N, P and K. If any minor elements are deficient, this will decrease yield and crop quality, but toxicities can also occur when concentrations are too high. This assessment's minor elements rating indicates whether four measured micronutrients (magnesium, iron, manganese, and zinc) are deficient or excessive.

Micronutrient availability is strongly influenced by pH and organic matter. Low pH increases the availability of most micronutrients, whereas high pH increases the availability of molybdenum, magnesium and calcium. High OM and microbial activity tend to increase micronutrient availability. Note that this test does not measure all important micronutrients. Consider submitting a sample for a complete micronutrient analysis to find out the levels of the other micronutrients.

Your measured Minor Elements Rating is **56**. This score is in the **Medium** range. Magnesium (410.7 ppm) is sufficient, Iron (0.4 ppm) is sufficient, Manganese (8.4 ppm) is sufficient, Zinc (0.2 ppm) is deficient. **This suggests that, while Minor Elements is functioning at an average level, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning. Soil management should aim at improving this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.** Please refer to the management suggestions table at the end of this document.

Overall Quality Score: an overall quality score is computed from the individual indicator scores. This score is further rated as follows: less than 20% is regarded as very low, 20-40% is low, 40-60% is medium, 60-80% is high, and greater than 80% is very high. The highest possible quality score is 100 and the least score is 0, thus it is a relative overall soil health status indicator. However, of greater importance than a single overall metric is identification of constrained or suboptimally functioning soil processes, so that these issues can be addressed through appropriate management. The overall soil quality score should be taken as a general summary rather than the main focus.

Your Overall Quality Score is **61**, which is in the **High** range.

Management Suggestions for Physical and Biological Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Predicted Available Water Capacity Low	• Add stable organic materials, mulch • Add compost or biochar • Incorporate high biomass cover crop	• Reduce tillage • Rotate with sod crops • Incorporate high biomass cover crop
Aggregate Stability Low	• Incorporate fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage • Use a surface mulch • Rotate with sod crops and mycorrhizal hosts
Organic Matter Low	• Add stable organic materials, mulch • Add compost and biochar • Incorporate high biomass cover crop	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Incorporate high biomass cover crop
ACE Soil Protein Index Low	• Add N-rich organic matter (low C:N source like manure, high N well-finished compost) • Incorporate young, green, cover crop biomass • Plant legumes and grass-legume mixtures • Inoculate legume seed with Rhizobia & check for nodulation	• Reduce tillage • Rotate with forage legume sod crop • Cover crop and add fresh manure • Keep pH at 6.2-6.5 (helps N fixation) • Monitor C:N ratio of inputs
Soil Respiration Low	• Maintain plant cover throughout season • Add fresh organic materials • Add manure, green manure • Consider reducing biocide usage	• Reduce tillage/mechanical cultivation • Increase rotational diversity • Maintain plant cover throughout season • Cover crop with symbiotic host plants
Active Carbon Low	• Add fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Cover crop whenever possible

Management Suggestions for Chemical Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Soil pH Low	• Add lime or wood ash per soil test recommendations • Add calcium sulfate (gypsum) in addition to lime if aluminum is high • Use less ammonium or urea	• Test soil annually & add "maintenance" lime per soil test recommendations to keep pH in range • Raise organic matter to improve buffering capacity
Soil pH High	• Stop adding lime or wood ash Add elemental sulfur per soil test recommendations	• Test soil annually • Use higher % ammonium or urea
Extractable Phosphorus Low	• Add P amendments per soil test recommendations • Use cover crops to recycle fixed P • Adjust pH to 6.2-6.5 to free up fixed P	• Promote mycorrhizal populations • Maintain a pH of 6.2-6.5 • Use cover crops to recycle fixed P
Extractable Phosphorus High	• Stop adding manure and compost • Choose low or no-P fertilizer blend • Apply only 20 lbs/ac starter P if needed • Apply P at or below crop removal rates	• Use cover crops that accumulate P and export to low P fields or offsite • Consider low P rations for livestock • Consider phytase for non-ruminants
Extractable Potassium Low	• Add wood ash, fertilizer, manure, or compost per soil test recommendations • Use cover crops to recycle K • Choose a high K fertilizer blend	• Use cover crops to recycle K • Add "maintenance" K per soil recommendations each year to keep K consistently available
Minor Elements Low	• Add chelated micros per soil test recommendations • Use cover crops to recycle micronutrients • Do not exceed pH 6.5 for most crops	• Promote mycorrhizal populations • Improve organic matter • Decrease soil P (binds micros)
Minor Elements High	• Raise pH to 6.2-6.5 (for all high micros • except Molybdenum) • Do not use fertilizers with micronutrients	• Maintain a pH of 6.2-6.5 • Monitor irrigation/improve drainage • Improve soil calcium levels

School of Integrative Plant Science, Soil and Crop Sciences Section, G01 Bradfield Hall, 306 Tower Road, Cornell University, Ithaca, NY 14853, email: soilhealth@cornell.edu

College of Agriculture and Life Sciences, Cornell University Developed in partnership with Cornell Soil Health, Farmier, and GreenStart.

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:	VVV1654
		Field ID:	Monticello Soil
		Date Sampled:	10/11/2021
		Tillage:	no till

Measured Soil Textural Class: **sandy loam**
Sand: **75%** - Silt: **14%** - Clay: **9%**

Group	Indicator	Value	Rating	Constraints
physical	Predicted Available Water Capacity	**0.16**	**64**	
physical	Surface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Subsurface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Aggregate Stability	**9.7**	**11**	Aeration, Infiltration, Rooting, Crusting, Sealing, Erosion, Runoff
biological	Organic Matter Soil Organic Carbon: 1.78 / Total Carbon: 1.89 / Total Nitrogen: 0.13	**2.2**	**60**	
biological	ACE Soil Protein Index	**4.7**	**22**	
biological	Soil Respiration	**0.4**	**29**	
biological	Active Carbon	**455**	**51**	
chemical	Soil pH	**7.4**	**96**	
chemical	Extractable Phosphorus	**5.2**	**100**	
chemical	Extractable Potassium	**49.6**	**74**	
chemical	Minor Elements Mg: 214.2 / Fe: 0.1 / Mn: 3.0 / Zn: 2.2		**100**	

Overall Quality Score: **61** / High

Measured Soil Health Indicators

The Cornell Soil Health Test measures several indicators of soil physical, biological and chemical health. These are listed on the left side of the report summary, on the first page. The "value" column shows each result as a value, measured in the laboratory or in the field, in units of measure as described in the indicator summaries below. The "rating" column interprets that measured value on a scale of 0 to 100, where higher scores are better. Ratings in red are particularly important to take note of, but any in yellow, particularly those that are close to a rating of 30 are also important in addressing soil health problems.

- **A rating below 20 indicates *Very Low (constraining)* functioning and is color-coded red.** This indicates a problem that is likely limiting yields, crop quality, and long-term sustainability of the agroecosystem. In several cases this indicates risks of environmental loss as well. The "constraint" column provides a short list of soil processes that are not functioning optimally when an indicator rating is red. It is particularly important to take advantage of any opportunities to improve management that will address these constraints.

- **A rating between 20 and 40 indicates *Low* functioning and is color-coded orange.** This indicates that a soil process is functioning somewhat poorly and addressing this should be considered in the field management plan. The Management Suggestions Table at the end of the Soil Health Assessment Report provides linkages to field management practices that are useful in addressing each soil indicator process.

- **A rating between 40 and 60 indicates *Medium* functioning and is color-coded yellow.** This indicates that soil health could be better, and yield and sustainability could decrease over time if this is not addressed. This is especially so if the condition is being caused, or not being alleviated, by current management. Pay attention particularly to those indicators rated in yellow and close to 40.

- **A rating** between **60 and 80 indicates *High* functioning and is color-coded light green.** This indicates that this soil process is functioning at a non-limiting level. Field soil management approaches should be maintained at the current intensity or improved.

- **A rating of 80 or greater indicates *Very High* functioning and is color-coded dark green.** Past management has been effective at maintaining soil health. It can be useful to note which particular aspects of management have likely maintained soil health, so that such management can be continued. Note that soil health is often high, when first converting from a permanent sod or forest. In these situations, intensive management quickly damages soil health when it includes intensive tillage, low organic matter inputs, bare soils for significant parts of the year, or excessive traffic, especially during wet times.

The Overall Quality Score at the bottom of the report is an average of all ratings, and provides an indication of the soil's overall health status. However, the important part is to know which particular soil processes are constrained or suboptimal so that these issues can be addressed through appropriate management. Therefore the ratings for each indicator are more important information.

The Indicators measured in the Cornell Soil Health Assessment are important soil properties and characteristics in themselves, but also are representative of key soil processes, necessary for the proper functioning of the soil. The following is a summary of the indicators measured, what each of these indicates about your soil's health status, and what may influence the relevant properties and processes described.

A Management Suggestions Table follows, at the end of the report, with short- and long-term suggestions for addressing constraints or maintaining a well-functioning system. This table will indicate constraints identified in this assessment for your soil sample by the same yellow and red color coding described above. Please also find further useful information by following the links to relevant publications and web resources that follow this section.

Texture is an inherent property of soil, meaning that it is rarely changed by management. It is thus not a soil health indicator *per se* but is helpful both in interpreting the measured values of indicators (see the Cornell Soil Health Assessment Training Manual), and for deciding on appropriate management strategies that will work for that soil.

Your soil's measured textural class and composition: sandy loam Sand: 75% Silt: 14% Clay: 9%

Predicted Available Water Capacity (AWC) is not a directly measured soil property but is modeled from a suite of measured soil health indicators including the percent sand, silt, clay and organic matter. By using a decision tree approach, the developed Random Forest model can predict the laboratory measured AWC value with no more error than that encountered in the raw laboratory analysis. Details of this modeling effort can be found in our Soil Health Management Series Fact Sheet Number 19-05b.

The Soil Health Lab continues to offer the laboratory measured AWC test as an add-on to the soil health package analyses.

The Predicted AWC value is presented as grams of water per gram of soil. This value is scored against an observed distribution in regional soils with similar texture. A physical soil characteristic, AWC is an indicator of the amount of plant-available water the soil can store, and therefore how crops will fare in droughty conditions. Soils with lower storage capacity will cause greater risk of drought stress. AWC is generally lower when total organic matter and/or aggregation is low. It can be improved by reducing tillage, long-term cover cropping, and adding large amounts of well-decomposed organic matter such as compost. Coarse textured (sandy) soils inherently store less water than finer textured soils, so that managing for relatively high water storage capacity is particularly important in coarse textured soils. While the textural effect cannot be influenced by management, management decisions can be in part based on an understanding of inherent soil characteristics.

Your Predicted Available Water Capacity value is **0.16 g/g**, corresponding with a score of **64**. This score is in the **High** range, relative to soils with similar texture. **This suggests that this soil process is enhancing overall soil resilience. Soil management should aim at maintaining this functionality while addressing any other measured soil**

constraints as identified in the Soil Health Assessment Report. Please refer to the management suggestions table at the end of this document.

Aggregate Stability is a measure of how well soil aggregates or crumbs hold together under rainfall or other rapid wetting stresses. Measured by the fraction of dried aggregates that disintegrate under a controlled, simulated rainfall event similar in energy delivery to a hard spring rain, the value is presented as a percent and scored against a distribution observed in regional soils with similar textural characteristics. A physical characteristic of soil, Aggregate Stability is a good indicator of soil biological and physical health. Good aggregate stability helps prevent crusting, runoff, and erosion, and facilitates aeration, infiltration, and water storage, along with improving seed germination and root and microbial health. Aggregate stability is influenced by microbial activity, as aggregates are largely held together by microbial colonies and exudates, and is impacted by management practices, particularly tillage, cover cropping, and fresh organic matter additions.

Your measured Aggregate Stability value is **9.7 %**, corresponding with a score of **11**. This score is in the **Very Low (constraining)** range, relative to soils with similar texture. **Aggregate Stability level should be given a high priority in management decisions based on this assessment, as it is likely to be an important constraint to proper soil functioning and sustainability of management at this time.** Please refer to the management suggestions table at the end of this document.

Organic Matter (OM) is a measure of the carbonaceous material in the soil that is biomass or biomass-derived. Measured by the mass lost on combustion of oven-dried soil, the value is presented as a percent of the total soil mass. This is scored against an observed distribution of OM in regional soils with similar texture. A soil characteristic that measures a physical substance of biological origin, OM is a key or central indicator of the physical, biological, and chemical health of the soil. OM content is an important influence on soil aggregate stabilization, water retention, nutrient cycling, and ion exchange capacity. Soils with low organic matter tend to require higher inputs, and be less resilient to drought and extreme rainfall. The retention and accumulation of OM is influenced by management practices such as tillage and cover cropping, as well as by microbial community growth. Intensive tillage and lack of organic matter biomass additions from various sources (amendments, residues, active crop or cover crop growth) will decrease organic matter content and overall soil health with time.

Total Carbon (Tot C) is an indicator for the OM in soil, with carbon comprising 48-58% of the total weight of OM. The Tot C analysis measures all of the carbon in a sample using complete oxidation of carbon to CO2 using high temperature combustion (1100C). The measured Tot C includes ***organic*** forms of carbon (Soil Organic Carbon SOC), comprised of available carbon as well as relatively inert carbon in stable organic materials. Carbon can also be found in ***inorganic*** form (Soil Inorganic Carbon SIC) as carbonate minerals such as calcium carbonate (lime).

Soil Organic Carbon (SOC) is equivalent to Tot C when there are no carbonate minerals. However, soils above pH 6.5 may contain high levels of carbonates. These carbonates are measured as SIC and subtracted from the Tot C: **SOC = Tot C - SIC**.

Total Nitrogen (Tot N) includes the organic (living and non-living) and inorganic (or mineral) forms of nitrogen. About half of the Tot N found in soil is in relatively stable organic compounds. Inorganic nitrogen is liberated from organic nitrogen sources in the soil, particularly proteins and amino acids through the action of soil microorganisms. Ammonium (NH_4^+) and nitrate (NO_3^-) are the inorganic forms of nitrogen found in soil that are plant available. The Tot N is determined following the combustion methodology known as DUMAS.

> **Your measured Organic Matter value** is **2.2 %**, corresponding with a score of **60**. This score is in the **High** range, relative to soils with similar texture. **This suggests that this soil process is enhancing overall soil resilience. Soil management should aim at maintaining this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.** Please refer to the management suggestions table at the end of this document. The **SOC** level is **1.78%**, the **Tot C** level is **1.89%**, the **Tot N** level is **0.13%**.

Soil Proteins are the fraction of the soil organic matter that are present as proteins or protein-like substances. This represents the large pool of organically bound N in the SOM, which microbial activity can mineralize, and make available for plant uptake. Measured by extraction with a citrate buffer under high temperature and pressure (hence Autoclave Citrate Extractable, or ACE proteins), the value given is expressed in mg extracted per gram of soil. As the method used extracts only a readily extractable fraction of the total amount of soil proteins in the SOM, we present this value as an index rather than as an absolute quantity. A measure of a physical substance, protein content is an indicator of the biological and chemical health of the soil, and is very well associated with overall soil health status. Protein content, as organically bound N, influences the ability of the soil to make N available by mineralization, and has been associated with soil aggregation and water movement. Protein content can be influenced by biomass additions, the presence of roots and soil microbes, and tends to decrease with increasing soil disturbance such as tillage.

> **Your measured ACE Soil Protein Index value** is **4.7,** corresponding with a score of **22**. This score is in the **Low** range, relative to soils with similar texture. **This suggests that, while ACE Soil Protein Index does not currently register as a strong constraint, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning.** Please refer to the management suggestions table at the end of this document.

Soil Respiration is a measure of the metabolic activity of the soil microbial community. Measured by capturing and quantifying carbon dioxide (CO_2) produced by this activity, the value is expressed as total CO_2 released (in mg) per gram of soil over a 4-day incubation period.

Respiration is scored against an observed distribution in regional soils, taking texture into account. A direct biological activity measurement, respiration is an indicator of the biological status of the soil community, integrating abundance and activity of microbial life. Soil biological activity accomplishes numerous important functions, such as cycling of nutrients into and out of soil OM pools, transformations of N between its several forms, and decomposition of incorporated residues. Soil biological activity influences key physical characteristics like OM accumulation, and aggregate formation and stabilization. Microbial activity is influenced by management practices such as tillage, cover cropping, manure or green manure incorporation, and biocide (pesticide, fungicide, herbicide) use.

> **Your measured Soil Respiration value** is **0.4 mg**, corresponding with a score of **29**. This score is in the **Low** range, relative to soils with similar texture. **This suggests that, while Soil Respiration does not currently register as a strong constraint, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning.** Please refer to the management suggestions table at the end of this document.

Active Carbon is a measure of the small portion of the organic matter that can serve as an easily available food source for soil microbes, thus helping maintain a healthy soil food web. Measured by potassium permanganate oxidation, the value is presented in parts per million (ppm), and scored against an observed distribution in regional soils with similar texture. While a measure of a class of physical substances, active carbon is a good leading indicator of biological soil health and tends to respond to changes in management earlier than total organic matter content, because when a large population of soil microbes is fed plentifully with enough organic matter over an extended period of time, well-decomposed organic matter builds up. A healthy and diverse microbial community is essential to maintain disease resistance, nutrient cycling, aggregation, and many other important functions. Intensive tillage and lack of organic matter additions from various sources (amendments, residues, active crop or cover crop growth) will decrease active carbon, and thus will over the longer term decrease total organic matter.

> **Your measured Active Carbon value** is **455 ppm**, corresponding with a score of **51**. This score is in the **Medium** range, relative to soils with similar texture. **This suggests that, while Active Carbon is functioning at an average level, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning. Soil management should aim at improving this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.** Please refer to the management suggestions table at the end of this document.

Soil pH is a measure of how acidic the soil is, which controls how available nutrients are to crops. A physico-chemical characteristic of soils, pH is an indicator of the chemical or nutrient status of the soil. Measured with an electrode in a 1:1 soil:water suspension, the value is presented in standard pH units, and scored using an optimality curve. Optimum pH is around 6.2-6.8 for most crops (exceptions include potatoes and blueberries, which grow best in more acidic soil – this is not accounted for in the report interpretation). If pH is too high, nutrients such as phosphorus, iron, manganese, copper and boron become unavailable to the crop. If pH is too low, calcium, magnesium, phosphorus, potassium and molybdenum become unavailable. Lack of nutrient availability will limit crop yields and quality. Aluminum toxicity can also be a concern in low pH soils, which can severely decrease root growth and yield, and in some cases lead to accumulation of aluminum and other metals in crop tissue. In general, as soil OM increases, crops can tolerate lower soil pH. Soil pH also influences the ability of certain pathogens to thrive, and of beneficial organisms to effectively colonize roots. Raising the pH through lime or wood ash applications, and organic matter additions, will help immobilize aluminum and heavy metals, and maintain proper nutrient availability.

> **Your measured Soil pH value** is **7.4,** corresponding with a score of **96**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Extractable Phosphorus is a measure of phosphorus (P) availability to a crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm), and scored against an optimality curve for sufficiency or excess. P is an essential plant macronutrient, and its availability varies with soil pH and mineral composition. Low P values indicate poor P availability to plants, and excessively high P values indicates a risk of adverse environmental impact through runoff and contamination of surface waters. Most soils in the Northeast store unavailable P from the soil's mineral make up or from previously applied fertilizer or manure. This becomes more available to plants as soils warm up. Therefore, incorporating or banding 10-25 lbs/acre of soluble 'starter' P fertilizer at planting can be useful even when soil levels are optimum. Some cover crops, such as buckwheat, are good at mining otherwise unavailable P so that it becomes more available to the following crop. When plants associate with mycorrhizal fungi, these can also help make P (and other nutrients and water) more available to the crop. P is an environmental contaminant and runoff of P into fresh surface water will cause damage through eutrophication, so over-application is strongly discouraged, especially close to surface water, on slopes, and on large scales.

> **Your measured Extractable Phosphorus value** is **5.2 ppm**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Extractable Potassium is a measure of potassium (K) availability to the crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm), and scored against an optimality curve for sufficiency. K is an indicator of soil nutrient status, as it is an essential plant macronutrient. Plants with higher potassium tend to be more tolerant of frost and cold. Thus, good potassium levels may help with season extension. While soil pH only marginally affects K availability, K is easily leached from sandy soils and is only weakly held by increased organic matter, so that applications of the amount removed by the specific crop being grown are generally necessary in such soils.

> **Your measured Extractable Potassium value** is **49.6 ppm**, corresponding with a score of **74**. This score is in the **High** range, relative to soils with similar texture. **This suggests that**

this soil process is enhancing overall soil resilience. Soil management should aim at maintaining this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.

Please refer to the management suggestions table at the end of this document.

Minor Elements, also called secondary (calcium, magnesium and sulfur) and micro (iron, manganese, zinc, copper, boron, molybdenum, etc.) nutrients are essential plant nutrients taken up by plants in smaller quantities than the macro nutrients N, P and K. If any minor elements are deficient, this will decrease yield and crop quality, but toxicities can also occur when concentrations are too high. This assessment's minor elements rating indicates whether four measured micronutrients (magnesium, iron, manganese, and zinc) are deficient or excessive.

Micronutrient availability is strongly influenced by pH and organic matter. Low pH increases the availability of most micronutrients, whereas high pH increases the availability of molybdenum, magnesium and calcium. High OM and microbial activity tend to increase micronutrient availability. Note that this test does not measure all important micronutrients. Consider submitting a sample for a complete micronutrient analysis to find out the levels of the other micronutrients.

Your measured Minor Elements Rating is **100**. This score is in the **Very High** range. Magnesium (214.2 ppm) is sufficient, Iron (0.1 ppm) is deficient, Manganese (3.0 ppm) is sufficient, Zinc (2.2 ppm) is sufficient. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Overall Quality Score: an overall quality score is computed from the individual indicator scores. This score is further rated as follows: less than 20% is regarded as very low, 20-40% is low, 40-60% is medium, 60-80% is high, and greater than 80% is very high. The highest possible quality score is 100 and the least score is 0, thus it is a relative overall soil health status indicator. However, of greater importance than a single overall metric is identification of constrained or suboptimally functioning soil processes, so that these issues can be addressed through appropriate management. The overall soil quality score should be taken as a general summary rather than the main focus.

Your Overall Quality Score is **61**, which is in the **High** range.

Management Suggestions for Physical and Biological Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Predicted Available Water Capacity Low	• Add stable organic materials, mulch • Add compost or biochar • Incorporate high biomass cover crop	• Reduce tillage • Rotate with sod crops • Incorporate high biomass cover crop
Aggregate Stability Low	• Incorporate fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage • Use a surface mulch • Rotate with sod crops and mycorrhizal hosts
Organic Matter Low	• Add stable organic materials, mulch • Add compost and biochar • Incorporate high biomass cover crop	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Incorporate high biomass cover crop
ACE Soil Protein Index Low	• Add N-rich organic matter (low C:N source like manure, high N well-finished compost) • Incorporate young, green, cover crop biomass • Plant legumes and grass-legume mixtures • Inoculate legume seed with Rhizobia & check for nodulation	• Reduce tillage • Rotate with forage legume sod crop • Cover crop and add fresh manure • Keep pH at 6.2-6.5 (helps N fixation) • Monitor C:N ratio of inputs
Soil Respiration Low	• • Maintain plant cover throughout season • Add fresh organic materials • Add manure, green manure • Consider reducing biocide usage	• Reduce tillage/mechanical cultivation • Increase rotational diversity • Maintain plant cover throughout season • Cover crop with symbiotic host plants
Active Carbon Low	• • Add fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Cover crop whenever possible

Management Suggestions for Chemical Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Soil pH Low	• Add lime or wood ash per soil test recommendations • Add calcium sulfate (gypsum) in addition to lime if aluminum is high • Use less ammonium or urea	• Test soil annually & add "maintenance" lime per soil test recommendations to keep pH in range • Raise organic matter to improve buffering capacity
Soil pH High	• Stop adding lime or wood ash • Add elemental sulfur per soil test recommendations	• Test soil annually • Use higher % ammonium or urea
Extractable Phosphorus Low	• Add P amendments per soil test recommendations • Use cover crops to recycle fixed P • Adjust pH to 6.2-6.5 to free up fixed P	• Promote mycorrhizal populations • Maintain a pH of 6.2-6.5 • Use cover crops to recycle fixed P
Extractable Phosphorus High	• Stop adding manure and compost • Choose low or no-P fertilizer blend • Apply only 20 lbs/ac starter P if needed • Apply P at or below crop removal rates	• Use cover crops that accumulate P and export to low P fields or offsite • Consider low P rations for livestock • Consider phytase for non-ruminants
Extractable Potassium Low	• Add wood ash, fertilizer, manure, or compost per soil test recommendations • Use cover crops to recycle K • Choose a high K fertilizer blend	• Use cover crops to recycle K • Add "maintenance" K per soil recommendations each year to keep K consistently available
Minor Elements Low	• Add chelated micros per soil test recommendations • Use cover crops to recycle micronutrients • Do not exceed pH 6.5 for most crops	• Promote mycorrhizal populations • Improve organic matter • Decrease soil P (binds micros)
Minor Elements High	• Raise pH to 6.2-6.5 (for all high micros except Molybdenum) • Do not use fertilizers with micronutrients	• Maintain a pH of 6.2-6.5 • Monitor irrigation/improve drainage • Improve soil calcium levels

School of Integrative Plant Science, Soil and Crop Sciences Section, G01 Bradfield Hall, 306 Tower Road, Cornell University, Ithaca, NY 14853, email: soilhealth@cornell.edu

College of Agriculture and Life Sciences, Cornell University Developed in partnership with Cornell Soil Health, Farmier, and GreenStart.

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:		Sample ID:	VVV1657
Bora Cetin centinbor@msu.edu		Field ID:	Ortonville Soil
		Date Sampled:	11/04/2021
		Tillage:	no till

Measured Soil Textural Class: **loam**

Sand: **27%** - Silt: **46%** - Clay: **26%**

Group	Indicator	Value	Rating	Constraints
physical	Predicted Available Water Capacity	**0.24**	**87**	
physical	Surface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Subsurface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Aggregate Stability	**7.7**	**9**	Aeration, Infiltration, Rooting, Crusting, Sealing, Erosion, Runoff
biological	Organic Matter Soil Organic Carbon: 2.72 / Total Carbon: 2.77 / Total Nitrogen: 0.22	**3.9**	**83**	
biological	ACE Soil Protein Index	**5.3**	**36**	
biological	Soil Respiration	**0.4**	**28**	
biological	Active Carbon	**598**	**70**	
chemical	Soil pH	**7.2**	**100**	
chemical	Extractable Phosphorus	**4.9**	**100**	
chemical	Extractable Potassium	**138.8**	**100**	
chemical	Minor Elements Mg: 633.8 / Fe: 0.1 / Mn: 4.0 / Zn: 0.4		**100**	

Overall Quality Score: 71 / High

Measured Soil Health Indicators

The Cornell Soil Health Test measures several indicators of soil physical, biological and chemical health. These are listed on the left side of the report summary, on the first page. The "value" column shows each result as a value, measured in the laboratory or in the field, in units of measure as described in the indicator summaries below. The "rating" column interprets that measured value on a scale of 0 to 100, where higher scores are better. Ratings in red are particularly important to take note of, but any in yellow, particularly those that are close to a rating of 30 are also important in addressing soil health problems.

- **A rating below 20 indicates *Very Low (constraining)* functioning and is color-coded red.** This indicates a problem that is likely limiting yields, crop quality, and long-term sustainability of the agroecosystem. In several cases this indicates risks of environmental loss as well. The "constraint" column provides a short list of soil processes that are not functioning optimally when an indicator rating is red. It is particularly important to take advantage of any opportunities to improve management that will address these constraints.
- **A rating between 20 and 40 indicates *Low* functioning and is color-coded orange.** This indicates that a soil process is functioning somewhat poorly and addressing this should be considered in the field management plan. The Management Suggestions Table at the end of the Soil Health Assessment Report provides linkages to field management practices that are useful in addressing each soil indicator process.
- **A rating between 40 and 60 indicates *Medium* functioning and is color-coded yellow.** This indicates that soil health could be better, and yield and sustainability could decrease over time if this is not addressed. This is especially so if the condition is being caused, or not being alleviated, by current management. Pay attention particularly to those indicators rated in yellow and close to 40.
- **A rating between 60 and 80 indicates *High* functioning and is color-coded light green.** This indicates that this soil process is functioning at a non-limiting level. Field soil management approaches should be maintained at the current intensity or improved.
- **A rating of 80 or greater indicates *Very High* functioning and is color-coded dark green.** Past management has been effective at maintaining soil health. It can be useful to note which particular aspects of management have likely maintained soil health, so that such management can be continued. Note that soil health is often high, when first converting from a permanent sod or forest. In these situations, intensive management quickly damages soil health when it includes intensive tillage, low organic matter inputs, bare soils for significant parts of the year, or excessive traffic, especially during wet times.
- **The Overall Quality Score** at the bottom of the report is an average of all ratings, and provides an indication of the soil's overall health status. However, the important part is to know which particular soil processes are constrained or suboptimal so that these issues can be addressed through appropriate management. Therefore the ratings for each indicator are more important information.

The Indicators measured in the Cornell Soil Health Assessment are important soil properties and characteristics in themselves, but also are representative of key soil processes, necessary for the proper functioning of the soil. The following is a summary of the indicators measured, what each of these indicates about your soil's health status, and what may influence the relevant properties and processes described.

A Management Suggestions Table follows, at the end of the report, with short and long term suggestions for addressing constraints or maintaining a well-functioning system. This table will indicate constraints identified in this assessment for your soil sample by the same yellow and red color coding described above. Please also find further useful information by following the links to relevant publications and web resources that follow this section.

Texture is an inherent property of soil, meaning that it is rarely changed by management. It is thus not a soil health indicator *per se* but is helpful both in interpreting the measured values of indicators (see the Cornell Soil Health Assessment Training Manual), and for deciding on appropriate management strategies that will work for that soil.

Your soil's measured textural class and composition: loam Sand: 27% Silt: 46% Clay: 26%

Predicted Available Water Capacity (AWC) is not a directly measured soil property but is modeled from a suite of measured soil health indicators including the percent sand, silt, clay and organic matter. By using a decision tree approach, the developed Random Forest model can predict the laboratory measured AWC value with no more error than that encountered in the raw laboratory analysis. Details of this modeling effort can be found in our Soil Health Management Series Fact Sheet Number 19-05b.

https://cpbe1.wpmucdn.com/blogs.cornell.edu/dist/f/5772/files/2016/12/05b_Soil_Health_Fact_S heet_Available_Water_Capacity-Predicted-2019-002-132f3th.pdf

The Soil Health Lab continues to offer the laboratory measured AWC test as an add-on to the soil health package analyses.

The Predicted AWC value is presented as grams of water per gram of soil. This value is scored against an observed distribution in regional soils with similar texture. A physical soil characteristic, AWC is an indicator of the amount of plant-available water the soil can store, and therefore how crops will fare in droughty conditions. Soils with lower storage capacity will cause greater risk of drought stress. AWC is generally lower when total organic matter and/or aggregation is low. It can be improved by reducing tillage, long-term cover cropping, and adding large amounts of well-decomposed organic matter such as compost. Coarse textured (sandy) soils inherently store less water than finer textured soils, so that managing for relatively high water storage capacity is particularly important in coarse textured soils. While the textural effect cannot be influenced by management, management decisions can be in part based on an understanding of inherent soil characteristics.

Your Predicted Available Water Capacity value is **0.24 g/g**, corresponding with a score of **87**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this**

condition, as it currently indicates ideal soil functioning. Please refer to the management suggestions table at the end of this document.

Aggregate Stability is a measure of how well soil aggregates or crumbs hold together under rainfall or other rapid wetting stresses. Measured by the fraction of dried aggregates that disintegrate under a controlled, simulated rainfall event similar in energy delivery to a hard spring rain, the value is presented as a percent, and scored against a distribution observed in regional soils with similar textural characteristics. A physical characteristic of soil, Aggregate Stability is a good indicator of soil biological and physical health. Good aggregate stability helps prevent crusting, runoff, and erosion, and facilitates aeration, infiltration, and water storage, along with improving seed germination and root and microbial health. Aggregate stability is influenced by microbial activity, as aggregates are largely held together by microbial colonies and exudates, and is impacted by management practices, particularly tillage, cover cropping, and fresh organic matter additions.

Your measured Aggregate Stability value is **7.7 %**, corresponding with a score of **9**. This score is in the **Very Low (constraining)** range, relative to soils with similar texture. **Aggregate Stability level should be given a high priority in management decisions based on this assessment, as it is likely to be an important constraint to proper soil functioning and sustainability of management at this time.** Please refer to the management suggestions table at the end of this document.

Organic Matter (OM) is a measure of the carbonaceous material in the soil that is biomass or biomass-derived. Measured by the mass lost on combustion of oven-dried soil, the value is presented as a percent of the total soil mass. This is scored against an observed distribution of OM in regional soils with similar texture. A soil characteristic that measures a physical substance of biological origin, OM is a key or central indicator of the physical, biological, and chemical health of the soil. OM content is an important influence on soil aggregate stabilization, water retention, nutrient cycling, and ion exchange capacity. Soils with low organic matter tend to require higher inputs, and be less resilient to drought and extreme rainfall. The retention and accumulation of OM is influenced by management practices such as tillage and cover cropping, as well as by microbial community growth. Intensive tillage and lack of organic matter biomass additions from various sources (amendments, residues, active crop or cover crop growth) will decrease organic matter content and overall soil health with time.

Total Carbon (Tot C) is an indicator for the OM in soil, with carbon comprising 48-58% of the total weight of OM. The Tot C analysis measures all of the carbon in a sample using complete oxidation of carbon to CO2 using high temperature combustion (1100C). The measured Tot C includes ***organic*** forms of carbon (Soil Organic Carbon SOC), comprised of available carbon as well as relatively inert carbon in stable organic materials. Carbon can also be found in ***inorganic*** form (Soil Inorganic Carbon SIC) as carbonate minerals such as calcium carbonate (lime).

Soil Organic Carbon (SOC) is equivalent to Tot C when there are no carbonate minerals. However, soils above pH 6.5 may contain high levels of carbonates. These carbonates are measured as SIC and subtracted from the Tot C: **SOC = Tot C - SIC**.

Total Nitrogen (Tot N) includes the organic (living and non-living) and inorganic (or mineral) forms of nitrogen. About half of the Tot N found in soil is in relatively stable organic compounds. Inorganic nitrogen is liberated from organic nitrogen sources in the soil, particularly proteins and amino acids through the action of soil microorganisms. Ammonium (NH4+) and nitrate (NO3-) are the inorganic forms of nitrogen found in soil that are plant available. The Tot N is determined following the combustion methodology known as DUMAS.

> **Your measured Organic Matter value** is **3.9 %**, corresponding with a score of **83**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document. The **SOC** level is **2.72%**, the **Tot C** level is **2.77%**, the **Tot N** level is **0.22%**.

Soil Proteins are the fraction of the soil organic matter that are present as proteins or protein-like substances. This represents the large pool of organically bound N in the SOM, which microbial activity can mineralize, and make available for plant uptake. Measured by extraction with a citrate buffer under high temperature and pressure (hence Autoclave Citrate Extractable, or ACE proteins), the value given is expressed in mg extracted per gram of soil. As the method used extracts only a readily extractable fraction of the total amount of soil proteins in the SOM, we present this value as an index rather than as an absolute quantity. A measure of a physical substance, protein content is an indicator of the biological and chemical health of the soil, and is very well associated with overall soil health status. Protein content, as organically bound N, influences the ability of the soil to make N available by mineralization, and has been associated with soil aggregation and water movement. Protein content can be influenced by biomass additions, the presence of roots and soil microbes, and tends to decrease with increasing soil disturbance such as tillage.

> **Your measured ACE Soil Protein Index value** is **5.3** , corresponding with a score of **36**. This score is in the **Low** range, relative to soils with similar texture. **This suggests that, while ACE Soil Protein Index does not currently register as a strong constraint, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning.** Please refer to the management suggestions table at the end of this document.

Soil Respiration is a measure of the metabolic activity of the soil microbial community. Measured by capturing and quantifying carbon dioxide (CO 2) produced by this activity, the value is expressed as total CO 2 released (in mg) per gram of soil over a 4 day incubation period.

Respiration is scored against an observed distribution in regional soils, taking texture into account. A direct biological activity measurement, respiration is an indicator of the biological status of the soil community, integrating abundance and activity of microbial life. Soil biological activity accomplishes numerous important functions, such as cycling of nutrients into and out of soil OM pools, transformations of N between its several forms, and decomposition of incorporated residues. Soil biological activity influences key physical characteristics like OM accumulation, and aggregate formation and stabilization. Microbial activity is influenced by management practices such as tillage, cover cropping, manure or green manure incorporation, and biocide (pesticide, fungicide, herbicide) use.

> **Your measured Soil Respiration value** is **0.4 mg**, corresponding with a score of **28**. This score is in the **Low** range, relative to soils with similar texture. **This suggests that, while Soil Respiration does not currently register as a strong constraint, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning.** Please refer to the management suggestions table at the end of this document.

Active Carbon is a measure of the small portion of the organic matter that can serve as an easily available food source for soil microbes, thus helping maintain a healthy soil food web. Measured by potassium permanganate oxidation, the value is presented in parts per million (ppm), and scored against an observed distribution in regional soils with similar texture. While a measure of a class of physical substances, active carbon is a good leading indicator of biological soil health and tends to respond to changes in management earlier than total organic matter content, because when a large population of soil microbes is fed plentifully with enough organic matter over an extended period of time, well-decomposed organic matter builds up. A healthy and diverse microbial community is essential to maintain disease resistance, nutrient cycling, aggregation, and many other important functions. Intensive tillage and lack of organic matter additions from various sources (amendments, residues, active crop or cover crop growth) will decrease active carbon, and thus will over the longer term decrease total organic matter.

> **Your measured Active Carbon value** is **598 ppm**, corresponding with a score of **70**. This score is in the **High** range, relative to soils with similar texture. **This suggests that this soil process is enhancing overall soil resilience. Soil management should aim at maintaining this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.** Please refer to the management suggestions table at the end of this document.

Soil pH is a measure of how acidic the soil is, which controls how available nutrients are to crops. A physico-chemical characteristic of soils, pH is an indicator of the chemical or nutrient status of the soil. Measured with an electrode in a 1:1 soil:water suspension, the value is presented in standard pH units, and scored using an optimality curve. Optimum pH is around 6.2-6.8 for most crops (exceptions include potatoes and blueberries, which grow best in more acidic soil – this is not accounted for in the report interpretation). If pH is too high, nutrients such as phosphorus, iron, manganese, copper and boron become unavailable to the crop. If pH is too low, calcium, magnesium, phosphorus, potassium and molybdenum become unavailable. Lack of nutrient availability will limit crop yields and quality. Aluminum toxicity can also be a concern in low pH soils, which can severely decrease root growth and yield, and in some cases lead to accumulation of aluminum and other metals in crop tissue. In general, as soil OM increases, crops can tolerate lower soil pH. Soil pH also influences the ability of certain pathogens to thrive, and of beneficial organisms to effectively colonize roots. Raising the pH through lime or wood ash applications, and organic matter additions, will help immobilize aluminum and heavy metals, and maintain proper nutrient availability.

> **Your measured Soil pH value** is **7.2,** corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Extractable Phosphorus is a measure of phosphorus (P) availability to a crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm) and scored against an optimality curve for sufficiency or excess. P is an essential plant macronutrient, and its availability varies with soil pH and mineral composition. Low P values indicate poor P availability to plants, and excessively high P values indicates a risk of adverse environmental impact through runoff and contamination of surface waters. Most soils in the Northeast store unavailable P from the soil's mineral make up or from previously applied fertilizer or manure. This becomes more available to plants as soils warm up. Therefore, incorporating or banding 10-25 lbs/acre of soluble 'starter' P fertilizer at planting can be useful even when soil levels are optimum. Some cover crops, such as buckwheat, are good at mining otherwise unavailable P so that it becomes more available to the following crop. When plants associate with mycorrhizal fungi, these can also help make P (and other nutrients and water) more available to the crop. P is an environmental contaminant and runoff of P into fresh surface water will cause damage through eutrophication, so over-application is strongly discouraged, especially close to surface water, on slopes, and on large scales.

> **Your measured Extractable Phosphorus value** is **4.9 ppm**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Extractable Potassium is a measure of potassium (K) availability to the crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm) and scored against an optimality curve for sufficiency. K is an indicator of soil nutrient status, as it is an essential plant macronutrient. Plants with higher potassium tend to be more tolerant of frost and cold. Thus, good potassium levels may help with season extension. While soil pH only marginally affects K availability, K is easily leached from sandy soils and is only weakly held by increased organic matter, so that applications of the amount removed by the specific crop being grown are generally necessary in such soils.

> **Your measured Extractable Potassium value** is **138.8 ppm**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Minor Elements, also called secondary (calcium, magnesium and sulfur) and micro (iron, manganese, zinc, copper, boron, molybdenum, etc.) nutrients are essential plant nutrients taken up by plants in smaller quantities than the macro nutrients N, P and K. If any minor elements are deficient, this will decrease yield and crop quality, but toxicities can also occur when concentrations are too high. This assessment's minor elements rating indicates whether four measured micronutrients (magnesium, iron, manganese, and zinc) are deficient or excessive.

Micronutrient availability is strongly influenced by pH and organic matter. Low pH increases the availability of most micronutrients, whereas high pH increases the availability of molybdenum, magnesium and calcium. High OM and microbial activity tend to increase micronutrient availability. Note that this test does not measure all important micronutrients. Consider submitting a sample for a complete micronutrient analysis to find out the levels of the other micronutrients.

> **Your measured Minor Elements Rating** is **100**. This score is in the **Very High** range. Magnesium (633.8 ppm) is sufficient, Iron (0.1 ppm) is deficient, Manganese (4.0 ppm) is sufficient, Zinc (0.4 ppm) is sufficient. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Overall Quality Score: an overall quality score is computed from the individual indicator scores. This score is further rated as follows: less than 20% is regarded as very low, 20-40% is low, 40-60% is medium, 60-80% is high, and greater than 80% is very high. The highest possible quality score is 100 and the least score is 0, thus it is a relative overall soil health status indicator. However, of greater importance than a single overall metric is identification of constrained or suboptimally functioning soil processes, so that these issues can be addressed through appropriate management. The overall soil quality score should be taken as a general summary rather than the main focus.

> **Your Overall Quality Score** is **71**, which is in the **High** range.

Management Suggestions for Physical and Biological Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Predicted Available Water Capacity Low	• Add stable organic materials, mulch • Add compost or biochar • Incorporate high biomass cover crop	• Reduce tillage • Rotate with sod crops • Incorporate high biomass cover crop
Aggregate Stability Low	• Incorporate fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage • Use a surface mulch • Rotate with sod crops and mycorrhizal hosts
Organic Matter Low	• Add stable organic materials, mulch • Add compost and biochar • Incorporate high biomass cover crop	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Incorporate high biomass cover crop
ACE Soil Protein Index Low	• Add N-rich organic matter (low C:N source like manure, high N well-finished compost) • Incorporate young, green, cover crop biomass • Plant legumes and grass-legume mixtures • Inoculate legume seed with Rhizobia & check for nodulation	• Reduce tillage • Rotate with forage legume sod crop • Cover crop and add fresh manure • Keep pH at 6.2-6.5 (helps N fixation) • Monitor C:N ratio of inputs
Soil Respiration Low	• Maintain plant cover throughout season • Add fresh organic materials • Add manure, green manure • Consider reducing biocide usage	• Reduce tillage/mechanical cultivation • Increase rotational diversity • Maintain plant cover throughout season • Cover crop with symbiotic host plants
Active Carbon Low	• Add fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Cover crop whenever possible

Management Suggestions for Chemical Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Soil pH Low	• Add lime or wood ash per soil test recommendations • Add calcium sulfate (gypsum) in addition to lime if aluminum is high • Use less ammonium or urea	• Test soil annually & add "maintenance" lime per soil test recommendations to keep pH in range • Raise organic matter to improve buffering capacity
Soil pH High	• Stop adding lime or wood ash • Add elemental sulfur per soil test recommendations	• Test soil annually • Use higher % ammonium or urea
Extractable Phosphorus Low	• Add P amendments per soil test recommendations • Use cover crops to recycle fixed P • Adjust pH to 6.2-6.5 to free up fixed P	• Promote mycorrhizal populations • Maintain a pH of 6.2-6.5 • Use cover crops to recycle fixed P
Extractable Phosphorus High	• Stop adding manure and compost • Choose low or no-P fertilizer blend • Apply only 20 lbs/ac starter P if needed • Apply P at or below crop removal rates	• Use cover crops that accumulate P and export to low P fields or offsite • Consider low P rations for livestock • Consider phytase for non-ruminants
Extractable Potassium Low	• Add wood ash, fertilizer, manure, or compost per soil test recommendations • Use cover crops to recycle K • Choose a high K fertilizer blend	• Use cover crops to recycle K • Add "maintenance" K per soil recommendations each year to keep K consistently available
Minor Elements Low	• Add chelated micros per soil test recommendations • Use cover crops to recycle micronutrients • Do not exceed pH 6.5 for most crops	• Promote mycorrhizal populations • Improve organic matter • Decrease soil P (binds micros)
Minor Elements High	• Raise pH to 6.2-6.5 (for all high micros except Molybdenum) • Do not use fertilizers with micronutrients	• Maintain a pH of 6.2-6.5 • Monitor irrigation/improve drainage • Improve soil calcium levels

School of Integrative Plant Science, Soil and Crop Sciences Section, G01 Bradfield Hall, 306 Tower Road, Cornell University, Ithaca, NY 14853, email: soilhealth@cornell.edu

College of Agriculture and Life Sciences, Cornell University Developed in partnership with Cornell Soil Health, Farmier, and GreenStart.

APPENDIX B

COMPOST AND BIOCHAR HEALTH REPORTS

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:		Sample ID:	VVV1661
Bora Cetin		Field ID:	Biochar
centinbor@msu.edu		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

Measured Soil Health Indicators

The Cornell Soil Health Test measures several indicators of soil physical, biological and chemical health. These are listed on the left side of the report summary, on the first page. The "value" column shows each result as a value, measured in the laboratory or in the field, in units of measure as described in the indicator summaries below. The "rating" column interprets that measured value on a scale of 0 to 100, where higher scores are better. Ratings in red are particularly important to take note of, but any in yellow, particularly those that are close to a rating of 30 are also important in addressing soil health problems.

- **A rating below 20 indicates *Very Low (constraining)* functioning and is color-coded red.** This indicates a problem that is likely limiting yields, crop quality, and long-term sustainability of the agroecosystem. In several cases this indicates risks of environmental loss as well. The "constraint" column provides a short list of soil processes that are not functioning optimally when an indicator rating is red. It is particularly important to take advantage of any opportunities to improve management that will address these constraints.

- **A rating between 20 and 40 indicates *Low* functioning and is color-coded orange.** This indicates that a soil process is functioning somewhat poorly and addressing this should be considered in the field management plan. The Management Suggestions Table at the end of the Soil Health Assessment Report provides linkages to field management practices that are useful in addressing each soil indicator process.
- **A rating between 40 and 60 indicates *Medium* functioning and is color-coded yellow.** This indicates that soil health could be better, and yield and sustainability could decrease over time if this is not addressed. This is especially so if the condition is being caused, or not being alleviated, by current management. Pay attention particularly to those indicators rated in yellow and close to 40.
- **A rating between 60 and 80 indicates *High* functioning and is color-coded light green.** This indicates that this soil process is functioning at a non-limiting level. Field soil management approaches should be maintained at the current intensity or improved.
- **A rat**ing of 80 or greater indicates Very High functioning and is color-coded dark green. Past management has been effective at maintaining soil health. It can be useful to note which particular aspects of management have likely maintained soil health, so that such management can be continued. Note that soil health is often high, when first converting from a permanent sod or forest. In these situations, intensive management quickly damages soil health when it includes intensive tillage, low organic matter inputs, bare soils for significant parts of the year, or excessive traffic, especially during wet times.
- The **Overall Quality Score** at the bottom of the report is an average of all ratings and provides an indication of the soil's overall health status. However, the important part is to know which particular soil processes are constrained or suboptimal so that these issues can be addressed through appropriate management. Therefore, the ratings for each indicator are more important information.

The Indicators measured in the Cornell Soil Health Assessment are important soil properties and characteristics in themselves, but also are representative of key soil processes, necessary for the proper functioning of the soil. The following is a summary of the indicators measured, what each of these indicates about your soil's health status, and what may influence the relevant properties and processes described.

A Management Suggestions Table follows, at the end of the report, with short and long term suggestions for addressing constraints or maintaining a well-functioning system. This table will indicate constraints identified in this assessment for your soil sample by the same yellow and red color coding described above. Please also find further useful information by following the links to relevant publications and web resources that follow this section.

Texture is an inherent property of soil, meaning that it is rarely changed by management. It is thus not a soil health indicator per se, but is helpful both in interpreting the measured values of indicators (see the Cornell Soil Health Assessment Training Manual), and for deciding on appropriate management strategies that will work for that soil.

Your soil's measured textural class and composition: clay Sand: --% Silt: 7% Clay: 91%

Predicted Available Water Capacity (AWC) is not a directly measured soil property but is modeled from a suite of measured soil health indicators including the percent sand, silt, clay and organic matter. By using a decision tree approach, the developed Random Forest model can predict the laboratory measured AWC value with no more error than that encountered in the raw laboratory analysis. Details of this modeling effort can be found in our Soil Health Management Series Fact Sheet Number 19-05b.

Soil Health Fact Sheet 19-05b: Predicted Available Water Capacity

The Soil Health Lab continues to offer the laboratory measured AWC test as an add-on to the soil health package analyses.

The Predicted AWC value is presented as grams of water per gram of soil. This value is scored against an observed distribution in regional soils with similar texture. A physical soil characteristic, AWC is an indicator of the amount of plant-available water the soil can store, and therefore how crops will fare in droughty conditions. Soils with lower storage capacity will cause greater risk of drought stress. AWC is generally lower when total organic matter and/or aggregation is low. It can be improved by reducing tillage, long-term cover cropping, and adding large amounts of well-decomposed organic matter such as compost. Coarse textured (sandy) soils inherently store less water than finer textured soils, so that managing for relatively high water storage capacity is particularly important in coarse textured soils. While the textural effect cannot be influenced by management, management decisions can be in part based on an understanding of inherent soil characteristics.

Your Predicted Available Water Capacity value is **0.27 g/g**, corresponding with a score of **95**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this**

condition, as it currently indicates ideal soil functioning. Please refer to the management suggestions table at the end of this document.

Aggregate Stability is a measure of how well soil aggregates or crumbs hold together under rainfall or other rapid wetting stresses. Measured by the fraction of dried aggregates that disintegrate under a controlled, simulated rainfall event similar in energy delivery to a hard spring rain, the value is presented as a percent, and scored against a distribution observed in regional soils with similar textural characteristics. A physical characteristic of soil, Aggregate Stability is a good indicator of soil biological and physical health. Good aggregate stability helps prevent crusting, runoff, and erosion, and facilitates aeration, infiltration, and water storage, along with improving seed germination and root and microbial health. Aggregate stability is influenced by microbial activity, as aggregates are largely held together by microbial colonies and exudates, and is impacted by management practices, particularly tillage, cover cropping, and fresh organic matter additions.

Your measured Aggregate Stability value is **94.0 %**, corresponding with a score of **99**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Organic Matter (OM) is a measure of the carbonaceous material in the soil that is biomass or biomass-derived. Measured by the mass lost on combustion of oven-dried soil, the value is presented as a percent of the total soil mass. This is scored against an observed distribution of OM in regional soils with similar texture. A soil characteristic that measures a physical substance of biological origin, OM is a key or central indicator of the physical, biological, and chemical health of the soil. OM content is an important influence on soil aggregate stabilization, water retention, nutrient cycling, and ion exchange capacity. Soils with low organic matter tend to require higher inputs, and be less resilient to drought and extreme rainfall. The retention and accumulation of OM is influenced by management practices such as tillage and cover cropping, as well as by microbial community growth. Intensive tillage and lack of organic matter biomass additions from various sources (amendments, residues, active crop or cover crop growth) will decrease organic matter content and overall soil health with time.

Total Carbon (Tot C) is an indicator for the OM in soil, with carbon comprising 48-58% of the total weight of OM. The Tot C analysis measures all of the carbon in a sample using complete oxidation of carbon to CO2 using high temperature combustion (1100C). The measured Tot C includes ***organic*** forms of carbon (Soil Organic Carbon SOC), comprised of available carbon as well as relatively inert carbon in stable organic materials. Carbon can also be found in ***inorganic*** form (Soil Inorganic Carbon SIC) as carbonate minerals such as calcium carbonate (lime).

Soil Organic Carbon (SOC) is equivalent to Tot C when there are no carbonate minerals. However, soils above pH 6.5 may contain high levels of carbonates. These carbonates are measured as SIC and subtracted from the Tot C: **SOC = Tot C - SIC**.

Total Nitrogen (Tot N) includes the organic (living and non-living) and inorganic (or mineral) forms of nitrogen. About half of the Tot N found in soil is in relatively stable organic compounds. Inorganic nitrogen is liberated from organic nitrogen sources in the soil, particularly proteins and amino acids through the action of soil microorganisms. Ammonium (NH4+) and nitrate (NO3-) are the inorganic forms of nitrogen found in soil that are plant available. The Tot N is determined following the combustion methodology known as DUMAS.

> **Your measured Organic Matter value** is **54.1 %**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document. The **SOC** level is **64.49%**, the **Tot C** level is **82.28%**, the **Tot N** level is **0.22%**.

Soil Proteins are the fraction of the soil organic matter that are present as proteins or protein-like substances. This represents the large pool of organically bound N in the SOM, which microbial activity can mineralize, and make available for plant uptake. Measured by extraction with a citrate buffer under high temperature and pressure (hence Autoclave Citrate Extractable, or ACE proteins), the value given is expressed in mg extracted per gram of soil. As the method used extracts only a readily extractable fraction of the total amount of soil proteins in the SOM, we present this value as an index rather than as an absolute quantity. A measure of a physical substance, protein content is an indicator of the biological and chemical health of the soil, and is very well associated with overall soil health status. Protein content, as organically bound N, influences the ability of the soil to make N available by mineralization, and has been associated with soil aggregation and water movement. Protein content can be influenced by biomass additions, the presence of roots and soil microbes, and tends to decrease with increasing soil disturbance such as tillage.

> **Your measured ACE Soil Protein Index value** is **0.3** , corresponding with a score of **2**. This score is in the **Very Low (constraining)** range, relative to soils with similar texture. **ACE Soil Protein Index level should be given a high priority in management decisions based on this assessment, as it is likely to be an important constraint to proper soil functioning and sustainability of management at this time.** Please refer to the management suggestions table at the end of this document.

Soil Respiration is a measure of the metabolic activity of the soil microbial community. Measured by capturing and quantifying carbon dioxide (CO 2) produced by this activity, the value is expressed as total CO 2 released (in mg) per gram of soil over a 4 day incubation period.

Respiration is scored against an observed distribution in regional soils, taking texture into account. A direct biological activity measurement, respiration is an indicator of the biological status of the soil community, integrating abundance and activity of microbial life. Soil biological activity accomplishes numerous important functions, such as cycling of nutrients into and out of soil OM pools, transformations of N between its several forms, and decomposition of incorporated residues. Soil biological activity influences key physical characteristics like OM accumulation, and aggregate formation and stabilization. Microbial activity is influenced by management practices such as tillage, cover cropping, manure or green manure incorporation, and biocide (pesticide, fungicide, herbicide) use.

> **Your measured Soil Respiration value** is **0.7 mg**, corresponding with a score of **68**. This score is in the **High** range, relative to soils with similar texture. **This suggests that this soil process is enhancing overall soil resilience. Soil management should aim at maintaining this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.** Please refer to the management suggestions table at the end of this document.

Active Carbon is a measure of the small portion of the organic matter that can serve as an easily available food source for soil microbes, thus helping maintain a healthy soil food web. Measured by potassium permanganate oxidation, the value is presented in parts per million (ppm), and scored against an observed distribution in regional soils with similar texture. While a measure of a class of physical substances, active carbon is a good leading indicator of biological soil health and tends to respond to changes in management earlier than total organic matter content, because when a large population of soil microbes is fed plentifully with enough organic matter over an extended period of time, well-decomposed organic matter builds up. A healthy and diverse microbial community is essential to maintain disease resistance, nutrient cycling, aggregation, and many other important functions. Intensive tillage and lack of organic matter additions from various sources (amendments, residues, active crop or cover crop growth) will decrease active carbon, and thus will over the longer term decrease total organic matter.

> **Your measured Active Carbon value** is **1396 ppm**, corresponding with a score of **99**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Soil pH is a measure of how acidic the soil is, which controls how available nutrients are to crops. A physico-chemical characteristic of soils, pH is an indicator of the chemical or nutrient status of the soil. Measured with an electrode in a 1:1 soil:water suspension, the value is presented in standard pH units, and scored using an optimality curve. Optimum pH is around 6.2-6.8 for most crops (exceptions include potatoes and blueberries, which grow best in more acidic soil – this is not accounted for in the report interpretation). If pH is too high, nutrients such as phosphorus, iron, manganese, copper and boron become unavailable to the crop. If pH is too low, calcium, magnesium, phosphorus, potassium and molybdenum become unavailable. Lack of nutrient availability will limit crop yields and quality. Aluminum toxicity can also be a concern in low pH soils, which can severely decrease root growth and yield, and in some cases lead to accumulation of aluminum and other metals in crop tissue. In general, as soil OM increases, crops can tolerate lower soil pH. Soil pH also influences the ability of certain pathogens to thrive, and of beneficial organisms to effectively colonize roots. Raising the pH through lime or wood ash applications, and organic matter additions, will help immobilize aluminum and heavy metals, and maintain proper nutrient availability.

Your measured Soil pH value is **9.0,** corresponding with a score of . This score is in the **Very Low (constraining)** range, relative to soils with similar texture. **Soil pH level should be given a high priority in management decisions based on this assessment, as it is likely to be an important constraint to proper soil functioning and sustainability of management at this time.** Please refer to the management suggestions table at the end of this document.

Extractable Phosphorus is a measure of phosphorus (P) availability to a crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm) and scored against an optimality curve for sufficiency or excess. P is an essential plant macronutrient, and its availability varies with soil pH and mineral composition. Low P values indicate poor P availability to plants, and excessively high P values indicates a risk of adverse environmental impact through runoff and contamination of surface waters. Most soils in the Northeast store unavailable P from the soil's mineral make up or from previously applied fertilizer or manure. This becomes more available to plants as soils warm up. Therefore, incorporating or banding 10-25 lbs/acre of soluble 'starter' P fertilizer at planting can be useful even when soil levels are optimum. Some cover crops, such as buckwheat, are good at mining otherwise unavailable P so that it becomes more available to the following crop. When plants associate with mycorrhizal fungi, these can also help make P (and other nutrients and water) more available to the crop. P is an environmental contaminant and runoff of P into fresh surface water will cause damage through eutrophication, so over-application is strongly discouraged, especially close to surface water, on slopes, and on large scales.

Your measured Extractable Phosphorus value is **599.2 ppm**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that while the current management practices have created a non- limiting condition, careful management should be applied to manage excessively high levels.** Please refer to the management suggestions table at the end of this document.

Extractable Potassium is a measure of potassium (K) availability to the crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm), and scored against an optimality curve for sufficiency. K is an indicator of soil nutrient status, as it is an essential plant macronutrient. Plants with higher potassium tend to be more tolerant of frost and cold. Thus, good potassium levels may help with season extension. While soil pH only marginally affects K availability, K is easily leached from sandy soils and is only weakly held by increased organic matter, so that applications of the amount removed by the specific crop being grown are generally necessary in such soils.

Your measured Extractable Potassium value is **3127.6 ppm**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Minor Elements, also called secondary (calcium, magnesium and sulfur) and micro (iron, manganese, zinc, copper, boron, molybdenum, etc.) nutrients are essential plant nutrients taken up by plants in smaller quantities than the macro nutrients N, P and K. If any minor elements are deficient, this will decrease yield and crop quality, but toxicities can also occur when concentrations are too high. This assessment's minor elements rating indicates whether four measured micronutrients (magnesium, iron, manganese, and zinc) are deficient or excessive.

Micronutrient availability is strongly influenced by pH and organic matter. Low pH increases the availability of most micronutrients, whereas high pH increases the availability of molybdenum, magnesium and calcium. High OM and microbial activity tend to increase micronutrient availability. Note that this test does not measure all important micronutrients. Consider submitting a sample for a complete micronutrient analysis to find out the levels of the other micronutrients.

> **Your measured Minor Elements Rating** is **56**. This score is in the **Medium** range. Magnesium (1729.7 ppm) is sufficient, Iron (4.8 ppm) is sufficient, Manganese (305.8 ppm) is excessive, Zinc (5.9 ppm) is sufficient. **This suggests that, while Minor Elements is functioning at an average level, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning. Soil management should aim at improving this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.** Please refer to the management suggestions table at the end of this document.

Overall Quality Score: an overall quality score is computed from the individual indicator scores. This score is further rated as follows: less than 20% is regarded as very low, 20-40% is low, 40-60% is medium, 60-80% is high, and greater than 80% is very high. The highest possible quality score is 100 and the least score is 0, thus it is a relative overall soil health status indicator. However, of greater importance than a single overall metric is identification of constrained or suboptimally functioning soil processes, so that these issues can be addressed through appropriate management. The overall soil quality score should be taken as a general summary rather than the main focus.

Your Overall Quality Score is 72, which is in the High range.

Management Suggestions for Physical and Biological Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Predicted Available Water Capacity Low	• Add stable organic materials, mulch • Add compost or biochar • Incorporate high biomass cover crop	• Reduce tillage • Rotate with sod crops • Incorporate high biomass cover crop
Aggregate Stability Low	• • Incorporate fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage • Use a surface mulch • Rotate with sod crops and mycorrhizal hosts
Organic Matter Low	• • Add stable organic materials, mulch • Add compost and biochar • Incorporate high biomass cover crop	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Incorporate high biomass cover crop
ACE Soil Protein Index Low	• Add N-rich organic matter (low C:N source like manure, high N well-finished compost) • Incorporate young, green, cover crop biomass • Plant legumes and grass-legume mixtures • Inoculate legume seed with Rhizobia & check for nodulation	• Reduce tillage • Rotate with forage legume sod crop • Cover crop and add fresh manure • Keep pH at 6.2-6.5 (helps N fixation) • Monitor C:N ratio of inputs
Soil Respiration Low	• Maintain plant cover throughout season • Add fresh organic materials • Add manure, green manure • Consider reducing biocide usage	• Reduce tillage/mechanical cultivation • Increase rotational diversity • Maintain plant cover throughout season • Cover crop with symbiotic host plants
Active Carbon Low	• • Add fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Cover crop whenever possible

Management Suggestions for Chemical Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Soil pH Low	• Add lime or wood ash per soil test recommendations • Add calcium sulfate (gypsum) in addition to lime if aluminum is high • Use less ammonium or urea	• Test soil annually & add "maintenance" lime per soil test recommendations to keep pH in range • Raise organic matter to improve buffering capacity
Soil pH High	• Stop adding lime or wood ash • Add elemental sulfur per soil test recommendations	• Test soil annually • Use higher % ammonium or urea
Extractable Phosphorus Low	• Add P amendments per soil test recommendations • Use cover crops to recycle fixed P • Adjust pH to 6.2-6.5 to free up fixed P	• Promote mycorrhizal populations • Maintain a pH of 6.2-6.5 • Use cover crops to recycle fixed P
Extractable Phosphorus High	• Stop adding manure and compost • Choose low or no-P fertilizer blend • Apply only 20 lbs/ac starter P if needed • Apply P at or below crop removal rates	• Use cover crops that accumulate P and export to low P fields or offsite • Consider low P rations for livestock • Consider phytase for non-ruminants
Extractable Potassium Low	• Add wood ash, fertilizer, manure, or compost per soil test recommendations • Use cover crops to recycle K • Choose a high K fertilizer blend	• Use cover crops to recycle K • Add "maintenance" K per soil recommendations each year to keep K consistently available
Minor Elements Low	• Add chelated micros per soil test recommendations • Use cover crops to recycle micronutrients • Do not exceed pH 6.5 for most crops	• Promote mycorrhizal populations • Improve organic matter • Decrease soil P (binds micros)
Minor Elements High	• • Raise pH to 6.2-6.5 (for all high micros except Molybdenum) • Do not use fertilizers with micronutrients	• Maintain a pH of 6.2-6.5 • Monitor irrigation/improve drainage • Improve soil calcium levels

School of Integrative Plant Science, Soil and Crop Sciences Section, G01 Bradfield Hall, 306 Tower Road, Cornell University, Ithaca, NY 14853, email: soilhealth@cornell.edu

College of Agriculture and Life Sciences, Cornell University Developed in partnership with Cornell Soil Health, Farmier, and GreenStart

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:		Sample ID:	VVV1660
Bora Cetin		Field ID:	Compost Grade 1
centinbor@msu.edu		Date Sampled:	10/25/2021
		Tillage:	no till

Measured Soil Textural Class: **clay**

Sand: **10%** - Silt: **20%** - Clay: **68%**

Group	Indicator	Value	Rating	Constraints
physical	Predicted Available Water Capacity	**0.29**	97	
physical	Surface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Subsurface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Aggregate Stability	**95.9**	99	
biological	Organic Matter Soil Organic Carbon: 30.52 / Total Carbon: 31.37 / Total Nitrogen: 2.93	**39.8**	100	
biological	ACE Soil Protein Index	**85.0**	100	
biological	Soil Respiration	**2.3**	99	
biological	Active Carbon	**979**	97	
chemical	Soil pH	**6.5**	100	
chemical	Extractable Phosphorus	**4841.2**	100	High Phosphorus, Environmental Impact Risk
chemical	Extractable Potassium	**22484.3**	100	
chemical	Minor Elements Mg: 4434.7 / Fe: 59.5 / Mn: 163.2 / Zn: 169.6		11	Deficient (element(s)) / Excessive (element(s))

Overall Quality Score: **90** / Very High

Measured Soil Health Indicators

The Cornell Soil Health Test measures several indicators of soil physical, biological and chemical health. These are listed on the left side of the report summary, on the first page. The "value" column shows each result as a value, measured in the laboratory or in the field, in units of measure as described in the indicator summaries below. The "rating" column interprets that measured value on a scale of 0 to 100, where higher scores are better. Ratings in red are particularly important to take note of, but any in yellow, particularly those that are close to a rating of 30 are also important in addressing soil health problems.

- **A rating below 20 indicates *Very Low (constraining)* functioning and is color-coded red.** This indicates a problem that is likely limiting yields, crop quality, and long-term sustainability of the agroecosystem. In several cases this indicates risks of environmental loss as well. The "constraint" column provides a short list of soil processes that are not functioning optimally when an indicator rating is red. It is particularly important to take advantage of any opportunities to improve management that will address these constraints.

- **A rating between 20 and 40 indicates *Low* functioning and is color-coded orange.** This indicates that a soil process is functioning somewhat poorly and addressing this should be considered in the field management plan. The Management Suggestions Table at the end of the Soil Health Assessment Report provides linkages to field management practices that are useful in addressing each soil indicator process.

- **A rating between 40 and 60 indicates *Medium* functioning and is color-coded yellow.** This indicates that soil health could be better, and yield and sustainability could decrease over time if this is not addressed. This is especially so if the condition is being caused, or not being alleviated, by current management. Pay attention particularly to those indicators rated in yellow and close to 40.

- **A rating between 60 and 80 indicates *High* functioning and is color-coded light green.** This indicates that this soil process is functioning at a non-limiting level. Field soil management approaches should be maintained at the current intensity or improved.

- **A rating of 80 or greater indicates *Very High* functioning and is color-coded dark green.** Past management has been effective at maintaining soil health. It can be useful to note which particular aspects of management have likely maintained soil health, so that such management can be continued. Note that soil health is often high, when first converting from a permanent sod or forest. In these situations, intensive management quickly damages soil health when it includes intensive tillage, low organic matter inputs, bare soils for significant parts of the year, or excessive traffic, especially during wet times.

- **The Overall Quality Score** at the bottom of the report is an average of all ratings, and provides an indication of the soil's overall health status. However, the important part is to know which particular soil processes are constrained or suboptimal so that these issues can be addressed through appropriate management. Therefore the ratings for each indicator are more important information.

The Indicators measured in the Cornell Soil Health Assessment are important soil properties and characteristics in themselves, but also are representative of key soil processes, necessary for the proper functioning of the soil. The following is a summary of the indicators measured, what each of these indicates about your soil's health status, and what may influence the relevant properties and processes described.

A Management Suggestions Table follows, at the end of the report, with short and long term suggestions for addressing constraints or maintaining a well-functioning system. This table will indicate constraints identified in this assessment for your soil sample by the same yellow and red color coding described above. Please also find further useful information by following the links to relevant publications and web resources that follow this section.

Texture is an inherent property of soil, meaning that it is rarely changed by management. It is thus not a soil health indicator *per se* but is helpful both in interpreting the measured values of indicators (see the Cornell Soil Health Assessment Training Manual), and for deciding on appropriate management strategies that will work for that soil.

Your soil's measured textural class and composition: clay Sand: 10% Silt: 20% Clay: 68%

Predicted Available Water Capacity (AWC) is not a directly measured soil property but is modeled from a suite of measured soil health indicators including the percent sand, silt, clay and organic matter. By using a decision tree approach, the developed Random Forest model can predict the laboratory measured AWC value with no more error than that encountered in the raw laboratory analysis. Details of this modeling effort can be found in our Soil Health Fact Sheet 19-05b: Predicted Available Water Capacity.

The Soil Health Lab continues to offer the laboratory measured AWC test as an add-on to the soil health package analyses.

The Predicted AWC value is presented as grams of water per gram of soil. This value is scored against an observed distribution in regional soils with similar texture. A physical soil characteristic, AWC is an indicator of the amount of plant-available water the soil can store, and therefore how crops will fare in droughty conditions. Soils with lower storage capacity will cause greater risk of drought stress. AWC is generally lower when total organic matter and/or aggregation is low. It can be improved by reducing tillage, long-term cover cropping, and adding large amounts of well-decomposed organic matter such as compost. Coarse textured (sandy) soils inherently store less water than finer textured soils, so that managing for relatively high water storage capacity is particularly important in coarse textured soils. While the textural effect cannot be influenced by management, management decisions can be in part based on an understanding of inherent soil characteristics.

Your Predicted Available Water Capacity value is **0.29 g/g**, corresponding with a score of **97**. This score is in the **Very High** range, relative to soils with similar texture. **This**

suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning. Please refer to the management suggestions table at the end of this document.

Aggregate Stability is a measure of how well soil aggregates or crumbs hold together under rainfall or other rapid wetting stresses. Measured by the fraction of dried aggregates that disintegrate under a controlled, simulated rainfall event similar in energy delivery to a hard spring rain, the value is presented as a percent, and scored against a distribution observed in regional soils with similar textural characteristics. A physical characteristic of soil, Aggregate Stability is a good indicator of soil biological and physical health. Good aggregate stability helps prevent crusting, runoff, and erosion, and facilitates aeration, infiltration, and water storage, along with improving seed germination and root and microbial health. Aggregate stability is influenced by microbial activity, as aggregates are largely held together by microbial colonies and exudates, and is impacted by management practices, particularly tillage, cover cropping, and fresh organic matter additions.

Your measured Aggregate Stability value is **95.9 %**, corresponding with a score of 99. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Organic Matter (OM) is a measure of the carbonaceous material in the soil that is biomass or biomass-derived. Measured by the mass lost on combustion of oven-dried soil, the value is presented as a percent of the total soil mass. This is scored against an observed distribution of OM in regional soils with similar texture. A soil characteristic that measures a physical substance of biological origin, OM is a key or central indicator of the physical, biological, and chemical health of the soil. OM content is an important influence on soil aggregate stabilization, water retention, nutrient cycling, and ion exchange capacity. Soils with low organic matter tend to require higher inputs, and be less resilient to drought and extreme rainfall. The retention and accumulation of OM is influenced by management practices such as tillage and cover cropping, as well as by microbial community growth. Intensive tillage and lack of organic matter biomass additions from various sources (amendments, residues, active crop or cover crop growth) will decrease organic matter content and overall soil health with time.

Total Carbon (Tot C) is an indicator for the OM in soil, with carbon comprising 48-58% of the total weight of OM. The Tot C analysis measures all of the carbon in a sample using complete oxidation of carbon to CO2 using high temperature combustion (1100C). The measured Tot C includes ***organic*** forms of carbon (Soil Organic Carbon SOC), comprised of available carbon as well as relatively inert carbon in stable organic materials. Carbon can also be found in ***inorganic*** form (Soil Inorganic Carbon SIC) as carbonate minerals such as calcium carbonate (lime).

Soil Organic Carbon (SOC) is equivalent to Tot C when there are no carbonate minerals. However, soils above pH 6.5 may contain high levels of carbonates. These carbonates are measured as SIC and subtracted from the Tot C: **SOC = Tot C - SIC**.

Total Nitrogen (Tot N) includes the organic (living and non-living) and inorganic (or mineral) forms of nitrogen. About half of the Tot N found in soil is in relatively stable organic compounds. Inorganic nitrogen is liberated from organic nitrogen sources in the soil, particularly proteins and amino acids through the action of soil microorganisms. Ammonium (NH_4^+) and nitrate (NO_3^-) are the inorganic forms of nitrogen found in soil that are plant available. The Tot N is determined following the combustion methodology known as DUMAS.

> **Your measured Organic Matter value** is **39.8 %**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document. The **SOC** level is **30.52%**, the **Tot C** level is **31.37%**, the **Tot N** level is **2.93%**.

Soil Proteins are the fraction of the soil organic matter that are present as proteins or protein-like substances. This represents the large pool of organically bound N in the SOM, which microbial activity can mineralize, and make available for plant uptake. Measured by extraction with a citrate buffer under high temperature and pressure (hence Autoclave Citrate Extractable, or ACE proteins), the value given is expressed in mg extracted per gram of soil. As the method used extracts only a readily extractable fraction of the total amount of soil proteins in the SOM, we present this value as an index rather than as an absolute quantity. A measure of a physical substance, protein content is an indicator of the biological and chemical health of the soil, and is very well associated with overall soil health status. Protein content, as organically bound N, influences the ability of the soil to make N available by mineralization, and has been associated with soil aggregation and water movement. Protein content can be influenced by biomass additions, the presence of roots and soil microbes, and tends to decrease with increasing soil disturbance such as tillage.

> **Your measured ACE Soil Protein Index value** is **85.0,** corresponding with a score of 100. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Soil Respiration is a measure of the metabolic activity of the soil microbial community. Measured by capturing and quantifying carbon dioxide (CO_2) produced by this activity, the value is expressed as total CO_2 released (in mg) per gram of soil over a 4 day incubation period.

Respiration is scored against an observed distribution in regional soils, taking texture into account. A direct biological activity measurement, respiration is an indicator of the biological status of the soil community, integrating abundance and activity of microbial life. Soil biological activity accomplishes numerous important functions, such as cycling of nutrients into and out of soil OM pools, transformations of N between its several forms, and decomposition of incorporated residues. Soil biological activity influences key physical characteristics like OM accumulation, and aggregate formation and stabilization. Microbial activity is influenced by management practices such as tillage, cover cropping, manure or green manure incorporation, and biocide (pesticide, fungicide, herbicide) use.

> **Your measured Soil Respiration value** is **2.3 mg**, corresponding with a score of **99**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Active Carbon is a measure of the small portion of the organic matter that can serve as an easily available food source for soil microbes, thus helping maintain a healthy soil food web. Measured by potassium permanganate oxidation, the value is presented in parts per million (ppm), and scored against an observed distribution in regional soils with similar texture. While a measure of a class of physical substances, active carbon is a good leading indicator of biological soil health and tends to respond to changes in management earlier than total organic matter content, because when a large population of soil microbes is fed plentifully with enough organic matter over an extended period of time, well-decomposed organic matter builds up. A healthy and diverse microbial community is essential to maintain disease resistance, nutrient cycling, aggregation, and many other important functions. Intensive tillage and lack of organic matter additions from various sources (amendments, residues, active crop or cover crop growth) will decrease active carbon, and thus will over the longer term decrease total organic matter.

> **Your measured Active Carbon value** is **979 ppm**, corresponding with a score of **97**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Soil pH is a measure of how acidic the soil is, which controls how available nutrients are to crops. A physico-chemical characteristic of soils, pH is an indicator of the chemical or nutrient status of the soil. Measured with an electrode in a 1:1 soil:water suspension, the value is presented in standard pH units, and scored using an optimality curve. Optimum pH is around 6.2-6.8 for most crops (exceptions include potatoes and blueberries, which grow best in more acidic soil – this is not accounted for in the report interpretation). If pH is too high, nutrients such as phosphorus, iron, manganese, copper and boron become unavailable to the crop. If pH is too low, calcium, magnesium, phosphorus, potassium and molybdenum become unavailable. Lack of nutrient availability will limit crop yields and quality. Aluminum toxicity can also be a concern in low pH soils, which can severely decrease root growth and yield, and in some cases lead to accumulation of aluminum and other metals in crop tissue. In general, as soil OM increases, crops can tolerate lower soil pH. Soil pH also influences the ability of certain pathogens to thrive, and of beneficial organisms to effectively colonize roots. Raising the pH through lime or wood ash applications, and organic matter additions, will help immobilize aluminum and heavy metals, and maintain proper nutrient availability.

Your measured Soil pH value is **6.5** , corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Extractable Phosphorus is a measure of phosphorus (P) availability to a crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm), and scored against an optimality curve for sufficiency or excess. P is an essential plant macronutrient, and its availability varies with soil pH and mineral composition. Low P values indicate poor P availability to plants, and excessively high P values indicates a risk of adverse environmental impact through runoff and contamination of surface waters. Most soils in the Northeast store unavailable P from the soil's mineral make up or from previously applied fertilizer or manure. This becomes more available to plants as soils warm up. Therefore, incorporating or banding 10-25 lbs/acre of soluble 'starter' P fertilizer at planting can be useful even when soil levels are optimum. Some cover crops, such as buckwheat, are good at mining otherwise unavailable P so that it becomes more available to the following crop. When plants associate with mycorrhizal fungi, these can also help make P (and other nutrients and water) more available to the crop. P is an environmental contaminant and runoff of P into fresh surface water will cause damage through eutrophication, so over-application is strongly discouraged, especially close to surface water, on slopes, and on large scales.

Your measured Extractable Phosphorus value is **4841.2 ppm**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that while the current management practices have created a non- limiting condition, careful management should be applied to manage excessively high levels.** Please refer to the management suggestions table at the end of this document.

Extractable Potassium is a measure of potassium (K) availability to the crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm) and scored against an optimality curve for sufficiency. K is an indicator of soil nutrient status, as it is an essential plant macronutrient. Plants with higher potassium tend to be more tolerant of frost and cold. Thus, good potassium levels may help with season extension. While soil pH only marginally affects K availability, K is easily leached from sandy soils and is only weakly held by increased organic matter, so that applications of the amount removed by the specific crop being grown are generally necessary in such soils.

Your measured Extractable Potassium value is **22484.3 ppm**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Minor Elements, also called secondary (calcium, magnesium and sulfur) and micro (iron, manganese, zinc, copper, boron, molybdenum, etc.) nutrients are essential plant nutrients taken up by plants in smaller quantities than the macro nutrients N, P and K. If any minor elements are deficient, this will decrease yield and crop quality, but toxicities can also occur when concentrations are too high. This assessment's minor elements rating indicates whether four measured micronutrients (magnesium, iron, manganese, and zinc) are deficient or excessive.

Micronutrient availability is strongly influenced by pH and organic matter. Low pH increases the availability of most micronutrients, whereas high pH increases the availability of molybdenum, magnesium and calcium. High OM and microbial activity tend to increase micronutrient availability. Note that this test does not measure all important micronutrients. Consider submitting a sample for a complete micronutrient analysis to find out the levels of the other micronutrients.

> **Your measured Minor Elements Rating** is **11**. This score is in the **Very Low (constraining)** range. Magnesium (4434.7 ppm) is sufficient, Iron (59.5 ppm) is excessive, Manganese (163.2 ppm) is excessive, Zinc (169.6 ppm) is excessive. **Minor Elements level should be given a high priority in management decisions based on this assessment, as it is likely to be an important constraint to proper soil functioning and sustainability of management at this time.** Please refer to the management suggestions table at the end of this document.

Overall Quality Score: an overall quality score is computed from the individual indicator scores. This score is further rated as follows: less than 20% is regarded as very low, 20-40% is low, 40-60% is medium, 60-80% is high, and greater than 80% is very high. The highest possible quality score is 100 and the least score is 0, thus it is a relative overall soil health status indicator. However, of greater importance than a single overall metric is identification of constrained or suboptimally functioning soil processes, so that these issues can be addressed through appropriate management. The overall soil quality score should be taken as a general summary rather than the main focus.

> **Your Overall Quality Score** is **90**, which is in the **Very High** range.

Management Suggestions for Physical and Biological Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Predicted Available Water Capacity Low	• Add stable organic materials, mulch • Add compost or biochar • Incorporate high biomass cover crop	• Reduce tillage • Rotate with sod crops • Incorporate high biomass cover crop
Aggregate Stability Low	• Incorporate fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage • Use a surface mulch • Rotate with sod crops and mycorrhizal hosts
Organic Matter Low	• • Add stable organic materials, mulch • Add compost and biochar • Incorporate high biomass cover crop	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Incorporate high biomass cover crop
ACE Soil Protein Index Low	• Add N-rich organic matter (low C:N source like manure, high N well-finished compost) • Incorporate young, green, cover crop biomass • Plant legumes and grass-legume mixtures • Inoculate legume seed with Rhizobia & check for nodulation	• Reduce tillage • Rotate with forage legume sod crop • Cover crop and add fresh manure • Keep pH at 6.2-6.5 (helps N fixation) • Monitor C:N ratio of inputs
Soil Respiration Low	• Maintain plant cover throughout season • Add fresh organic materials • Add manure, green manure • Consider reducing biocide usage	• Reduce tillage/mechanical cultivation • Increase rotational diversity • Maintain plant cover throughout season • Cover crop with symbiotic host plants
Active Carbon Low	• • Add fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Cover crop whenever possible

Management Suggestions for Chemical Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Soil pH Low	• Add lime or wood ash per soil test recommendations • Add calcium sulfate (gypsum) in addition to lime if aluminum is high • Use less ammonium or urea	• Test soil annually & add "maintenance" lime per soil test recommendations to keep pH in range • Raise organic matter to improve buffering capacity
Soil pH High	• Stop adding lime or wood ash • Add elemental sulfur per soil test recommendations	• Test soil annually • Use higher % ammonium or urea
Extractable Phosphorus Low	• Add P amendments per soil test recommendations • Use cover crops to recycle fixed P • Adjust pH to 6.2-6.5 to free up fixed P	• Promote mycorrhizal populations • Maintain a pH of 6.2-6.5 • Use cover crops to recycle fixed P
Extractable Phosphorus High	• Stop adding manure and compost • Choose low or no-P fertilizer blend • Apply only 20 lbs/ac starter P if needed • Apply P at or below crop removal rates	• Use cover crops that accumulate P and export to low P fields or offsite • Consider low P rations for livestock • Consider phytase for non-ruminants
Extractable Potassium Low	• Add wood ash, fertilizer, manure, or compost per soil test recommendations • Use cover crops to recycle K • Choose a high K fertilizer blend	• Use cover crops to recycle K • Add "maintenance" K per soil recommendations each year to keep K consistently available
Minor Elements Low	• Add chelated micros per soil test recommendations • Use cover crops to recycle micronutrients • Do not exceed pH 6.5 for most crops	• Promote mycorrhizal populations • Improve organic matter • Decrease soil P (binds micros)
Minor Elements High	• Raise pH to 6.2-6.5 (for all high micros except Molybdenum) • Do not use fertilizers with micronutrients	• Maintain a pH of 6.2-6.5 • Monitor irrigation/improve drainage • Improve soil calcium levels

School of Integrative Plant Science, Soil and Crop Sciences Section, G01 Bradfield Hall, 306 Tower Road, Cornell University, Ithaca, NY 14853, email: soilhealth@cornell.edu

College of Agriculture and Life Sciences, Cornell University Developed in partnership with Cornell Soil Health, Farmier, and GreenStart.

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:		Sample ID:	VVV1658
Bora Cetin		Field ID:	Food-waste Compost
centinbor@msu.edu		Date Sampled:	11/14/2021
		Tillage:	no till

Measured Soil Textural Class: **clay**
Sand: **37%** - Silt: **20%** - Clay: **42%**

Group	Indicator	Value	Rating	Constraints
physical	Predicted Available Water Capacity	**0.25**	91	
physical	Surface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Subsurface Hardness			Not rated: No Field Penetrometer Readings Submitted
physical	Aggregate Stability	**89.6**	99	
biological	Organic Matter Soil Organic Carbon: 17.99 / Total Carbon: 19.28 / Total Nitrogen: 1.49	**23.5**	100	
biological	ACE Soil Protein Index	**63.3**	100	
biological	Soil Respiration	**2.6**	100	
biological	Active Carbon	**1382**	99	
chemical	Soil pH	**7.6**	87	
chemical	Extractable Phosphorus	**649.9**	100	High Phosphorus, Environmental Impact Risk
chemical	Extractable Potassium	**6300.5**	100	
chemical	Minor Elements Mg: 2683.5 / Fe: 12.5 / Mn: 94.4 / Zn: 5.0		56	

Overall Quality Score: **93** / Very High

Measured Soil Health Indicators

The Cornell Soil Health Test measures several indicators of soil physical, biological and chemical health. These are listed on the left side of the report summary, on the first page. The "value" column shows each result as a value, measured in the laboratory or in the field, in units of measure as described in the indicator summaries below. The "rating" column interprets that measured value on a scale of 0 to 100, where higher scores are better. Ratings in red are particularly important to take note of, but any in yellow, particularly those that are close to a rating of 30 are also important in addressing soil health problems.

- **A rating below 20 indicates *Very Low (constraining)* functioning and is color-coded red.** This indicates a problem that is likely limiting yields, crop quality, and long-term sustainability of the agroecosystem. In several cases this indicates risks of environmental loss as well. The "constraint" column provides a short list of soil processes that are not functioning optimally when an indicator rating is red. It is particularly important to take advantage of any opportunities to improve management that will address these constraints.

- **A rating between 20 and 40 indicates *Low* functioning and is color-coded orange.** This indicates that a soil process is functioning somewhat poorly and addressing this should be considered in the field management plan. The Management Suggestions Table at the end of the Soil Health Assessment Report provides linkages to field management practices that are useful in addressing each soil indicator process.

- **A rating between 40 and 60 indicates *Medium* functioning and is color-coded yellow.** This indicates that soil health could be better, and yield and sustainability could decrease over time if this is not addressed. This is especially so if the condition is being caused, or not being alleviated, by current management. Pay attention particularly to those indicators rated in yellow and close to 40.
- **A rating between 60 and 80 indicates *High* functioning and is color-coded light green.** This indicates that this soil process is functioning at a non-limiting level. Field soil management approaches should be maintained at the current intensity or improved.

- **A rating of 80 or greater indicates *Very High* functioning and is color-coded dark green.** Past management has been effective at maintaining soil health. It can be useful to note which particular aspects of management have likely maintained soil health, so that such management can be continued. Note that soil health is often high, when first converting from a permanent sod or forest. In these situations, intensive management quickly damages soil health when it includes intensive tillage, low organic matter inputs, bare soils for significant parts of the year, or excessive traffic, especially during wet times.

- **The Overall Quality Score** at the bottom of the report is an average of all ratings, and provides an indication of the soil's overall health status. However, the important part is to know which particular soil processes are constrained or suboptimal so that these issues can be addressed through appropriate management. Therefore the ratings for each indicator are more important information.

The Indicators measured in the Cornell Soil Health Assessment are important soil properties and characteristics in themselves, but also are representative of key soil processes, necessary for the proper functioning of the soil. The following is a summary of the indicators measured, what each of these indicates about your soil's health status, and what may influence the relevant properties and processes described.

A Management Suggestions Table follows, at the end of the report, with short- and long-term suggestions for addressing constraints or maintaining a well-functioning system. This table will indicate constraints identified in this assessment for your soil sample by the same yellow and red color coding described above. Please also find further useful information by following the links to relevant publications and web resources that follow this section.

Texture is an inherent property of soil, meaning that it is rarely changed by management. It is thus not a soil health indicator *per se* but is helpful both in interpreting the measured values of indicators (see the Cornell Soil Health Assessment Training Manual), and for deciding on appropriate management strategies that will work for that soil.

Your soil's measured textural class and composition: clay and: 37% Silt: 20% Clay: 42%

Predicted Available Water Capacity (AWC) is not a directly measured soil property but is modeled from a suite of measured soil health indicators including the percent sand, silt, clay and organic matter. By using a decision tree approach, the developed Random Forest model can predict the laboratory measured AWC value with no more error than that encountered in the raw laboratory analysis. Details of this modeling effort can be found in our Soil Health Management Series Fact Sheet Number 19-05b.

The Soil Health Lab continues to offer the laboratory measured AWC test as an add-on to the soil health package analyses.

The Predicted AWC value is presented as grams of water per gram of soil. This value is scored against an observed distribution in regional soils with similar texture. A physical soil characteristic, AWC is an indicator of the amount of plant-available water the soil can store, and therefore how crops will fare in droughty conditions. Soils with lower storage capacity will cause greater risk of drought stress. AWC is generally lower when total organic matter and/or aggregation is low. It can be improved by reducing tillage, long-term cover cropping, and adding large amounts of well-decomposed organic matter such as compost. Coarse textured (sandy) soils inherently store less water than finer textured soils, so that managing for relatively high water storage capacity is particularly important in coarse textured soils. While the textural effect cannot be influenced by management, management decisions can be in part based on an understanding of inherent soil characteristics.

Your Predicted Available Water Capacity value is **0.25 g/g**, corresponding with a score of **91**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Aggregate Stability is a measure of how well soil aggregates or crumbs hold together under rainfall or other rapid wetting stresses. Measured by the fraction of dried aggregates that disintegrate under a controlled, simulated rainfall event similar in energy delivery to a hard spring rain, the value is presented as a percent, and scored against a distribution observed in regional soils with similar textural characteristics. A physical characteristic of soil, Aggregate Stability is a good indicator of soil biological and physical health. Good aggregate stability helps prevent crusting, runoff, and erosion, and facilitates aeration, infiltration, and water storage, along with improving seed germination and root and microbial health. Aggregate stability is influenced by microbial activity, as aggregates are largely held together by microbial colonies and exudates, and is impacted by management practices, particularly tillage, cover cropping, and fresh organic matter additions.

> **Your measured Aggregate Stability value** is **89.6 %**, corresponding with a score of 99. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Organic Matter (OM) is a measure of the carbonaceous material in the soil that is biomass or biomass-derived. Measured by the mass lost on combustion of oven-dried soil, the value is presented as a percent of the total soil mass. This is scored against an observed distribution of OM in regional soils with similar texture. A soil characteristic that measures a physical substance of biological origin, OM is a key or central indicator of the physical, biological, and chemical health of the soil. OM content is an important influence on soil aggregate stabilization, water retention, nutrient cycling, and ion exchange capacity. Soils with low organic matter tend to require higher inputs, and be less resilient to drought and extreme rainfall. The retention and accumulation of OM is influenced by management practices such as tillage and cover cropping, as well as by microbial community growth. Intensive tillage and lack of organic matter biomass additions from various sources (amendments, residues, active crop or cover crop growth) will decrease organic matter content and overall soil health with time.

Total Carbon (Tot C) is an indicator for the OM in soil, with carbon comprising 48-58% of the total weight of OM. The Tot C analysis measures all of the carbon in a sample using complete oxidation of carbon to CO2 using high temperature combustion (1100C). The measured Tot C includes ***organic*** forms of carbon (Soil Organic Carbon SOC), comprised of available carbon as well as relatively inert carbon in stable organic materials. Carbon can also be found in ***inorganic*** form (Soil Inorganic Carbon SIC) as carbonate minerals such as calcium carbonate (lime).

Soil Organic Carbon (SOC) is equivalent to Tot C when there are no carbonate minerals. However, soils above pH 6.5 may contain high levels of carbonates. These carbonates are measured as SIC and subtracted from the Tot C: **SOC = Tot C - SIC**.

Total Nitrogen (Tot N) includes the organic (living and non-living) and inorganic (or mineral) forms of nitrogen. About half of the Tot N found in soil is in relatively stable organic compounds. Inorganic nitrogen is liberated from organic nitrogen sources in the soil, particularly proteins and amino acids through the action of soil microorganisms. Ammonium (NH4+) and nitrate (NO3-) are the inorganic forms of nitrogen found in soil that are plant available. The Tot N is determined following the combustion methodology known as DUMAS.

Your measured Organic Matter value is **23.5 %**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document. The **SOC** level is **17.99%**, the **Tot C** level is **19.28%**, the **Tot N** level is **1.49%**.

Soil Proteins are the fraction of the soil organic matter that are present as proteins or protein-like substances. This represents the large pool of organically bound N in the SOM, which microbial activity can mineralize, and make available for plant uptake. Measured by extraction with a citrate buffer under high temperature and pressure (hence Autoclave Citrate Extractable, or ACE proteins), the value given is expressed in mg extracted per gram of soil. As the method used extracts only a readily extractable fraction of the total amount of soil proteins in the SOM, we present this value as an index rather than as an absolute quantity. A measure of a physical substance, protein content is an indicator of the biological and chemical health of the soil, and is very well associated with overall soil health status. Protein content, as organically bound N, influences the ability of the soil to make N available by mineralization, and has been associated with soil aggregation and water movement. Protein content can be influenced by biomass additions, the presence of roots and soil microbes, and tends to decrease with increasing soil disturbance such as tillage.

Your measured ACE Soil Protein Index value is **63.3** , corresponding with a score 99. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Soil Respiration is a measure of the metabolic activity of the soil microbial community. Measured by capturing and quantifying carbon dioxide (CO 2) produced by this activity, the value is expressed as total CO 2 released (in mg) per gram of soil over a 4 day incubation period.

Respiration is scored against an observed distribution in regional soils, taking texture into account. A direct biological activity measurement, respiration is an indicator of the biological status of the soil community, integrating abundance and activity of microbial life. Soil biological activity accomplishes numerous important functions, such as cycling of nutrients into and out of soil OM pools, transformations of N between its several forms, and decomposition of incorporated residues. Soil biological activity influences key physical characteristics like OM accumulation, and aggregate formation and stabilization. Microbial activity is influenced by management practices such as tillage, cover cropping, manure or green manure incorporation, and biocide (pesticide, fungicide, herbicide) use.

Your measured Soil Respiration value is **2.6 mg**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that**

management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning. Please refer to the management suggestions table at the end of this document.

Active Carbon is a measure of the small portion of the organic matter that can serve as an easily available food source for soil microbes, thus helping maintain a healthy soil food web. Measured by potassium permanganate oxidation, the value is presented in parts per million (ppm), and scored against an observed distribution in regional soils with similar texture. While a measure of a class of physical substances, active carbon is a good leading indicator of biological soil health and tends to respond to changes in management earlier than total organic matter content, because when a large population of soil microbes is fed plentifully with enough organic matter over an extended period of time, well-decomposed organic matter builds up. A healthy and diverse microbial community is essential to maintain disease resistance, nutrient cycling, aggregation, and many other important functions. Intensive tillage and lack of organic matter additions from various sources (amendments, residues, active crop or cover crop growth) will decrease active carbon, and thus will over the longer term decrease total organic matter. **Your measured Active Carbon value** is **1382 ppm**, corresponding with a score of **99**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Soil pH is a measure of how acidic the soil is, which controls how available nutrients are to crops. A physico-chemical characteristic of soils, pH is an indicator of the chemical or nutrient status of the soil. Measured with an electrode in a 1:1 soil:water suspension, the value is presented in standard pH units, and scored using an optimality curve. Optimum pH is around 6.2-6.8 for most crops (exceptions include potatoes and blueberries, which grow best in more acidic soil – this is not accounted for in the report interpretation). If pH is too high, nutrients such as phosphorus, iron, manganese, copper and boron become unavailable to the crop. If pH is too low, calcium, magnesium, phosphorus, potassium and molybdenum become unavailable. Lack of nutrient availability will limit crop yields and quality. Aluminum toxicity can also be a concern in low pH soils, which can severely decrease root growth and yield, and in some cases lead to accumulation of aluminum and other metals in crop tissue. In general, as soil OM increases, crops can tolerate lower soil pH. Soil pH also influences the ability of certain pathogens to thrive, and of beneficial organisms to effectively colonize roots. Raising the pH through lime or wood ash applications, and organic matter additions, will help immobilize aluminum and heavy metals, and maintain proper nutrient availability.

Your measured Soil pH value is **7.6,** corresponding with a score of **87**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Extractable Phosphorus is a measure of phosphorus (P) availability to a crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm), and scored against an optimality curve for sufficiency or excess. P is an essential plant macronutrient, and its availability varies with soil pH and mineral composition. Low P values indicate poor P availability to plants, and excessively high P values indicates a risk of adverse environmental impact through runoff and contamination of surface waters. Most soils in the Northeast store unavailable P from the soil's mineral make up or from previously applied fertilizer or manure. This becomes more available to plants as soils warm up. Therefore, incorporating or banding 10-25 lbs/acre of soluble 'starter' P fertilizer at planting can be useful even when soil levels are optimum. Some cover crops, such as buckwheat, are good at mining otherwise unavailable P so that it becomes more available to the following crop. When plants associate with mycorrhizal fungi, these can also help make P (and other nutrients and water) more available to the crop. P is an environmental contaminant and runoff of P into fresh surface water will cause damage through eutrophication, so over-application is strongly discouraged, especially close to surface water, on slopes, and on large scales.

> **Your measured Extractable Phosphorus value** is **649.9 ppm**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that while the current management practices have created a non- limiting condition, careful management should be applied to manage excessively high levels.** Please refer to the management suggestions table at the end of this document.

Extractable Potassium is a measure of potassium (K) availability to the crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm) and scored against an optimality curve for sufficiency. K is an indicator of soil nutrient status, as it is an essential plant macronutrient. Plants with higher potassium tend to be more tolerant of frost and cold. Thus, good potassium levels may help with season extension. While soil pH only marginally affects K availability, K is easily leached from sandy soils and is only weakly held by increased organic matter, so that applications of the amount removed by the specific crop being grown are generally necessary in such soils.

> **Your measured Extractable Potassium value** is **6300.5 ppm**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Minor Elements, also called secondary (calcium, magnesium and sulfur) and micro (iron, manganese, zinc, copper, boron, molybdenum, etc.) nutrients are essential plant nutrients taken up by plants in smaller quantities than the macro nutrients N, P and K. If any minor elements are deficient, this will decrease yield and crop quality, but toxicities can also occur when concentrations are too high. This assessment's minor elements rating indicates whether four measured micronutrients (magnesium, iron, manganese, and zinc) are deficient or excessive.

Micronutrient availability is strongly influenced by pH and organic matter. Low pH increases the availability of most micronutrients, whereas high pH increases the availability of molybdenum, magnesium and calcium. High OM and microbial activity tend to increase micronutrient availability. Note that this test does not measure all important micronutrients. Consider submitting a sample for a complete micronutrient analysis to find out the levels of the other micronutrients.

Your measured Minor Elements Rating is **56**. This score is in the **Medium** range. Magnesium (2683.5 ppm) is sufficient, Iron (12.5 ppm) is sufficient, Manganese (94.4 ppm) is excessive, Zinc (5.0 ppm) is sufficient. **This suggests that, while Minor Elements is functioning at an average level, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning. Soil management should aim at improving this functionality while addressing any other measured soil constraints as identified in the Soil Health Assessment Report.** Please refer to the management suggestions table at the end of this document.

Overall Quality Score: an overall quality score is computed from the individual indicator scores. This score is further rated as follows: less than 20% is regarded as very low, 20-40% is low, 40-60% is medium, 60-80% is high, and greater than 80% is very high. The highest possible quality score is 100 and the least score is 0, thus it is a relative overall soil health status indicator. However, of greater importance than a single overall metric is identification of constrained or suboptimally functioning soil processes, so that these issues can be addressed through appropriate management. The overall soil quality score should be taken as a general summary rather than the main focus.

Your Overall Quality Score is **93**, which is in the **Very High** range.

Management Suggestions for Physical and Biological Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Predicted Available Water Capacity Low	• Add stable organic materials, mulch • Add compost or biochar • Incorporate high biomass cover crop	• Reduce tillage • Rotate with sod crops • Incorporate high biomass cover crop
Aggregate Stability Low	• Incorporate fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage • Use a surface mulch • Rotate with sod crops and mycorrhizal hosts
Organic Matter Low	• Add stable organic materials, mulch • Add compost and biochar • Incorporate high biomass cover crop	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Incorporate high biomass cover crop
ACE Soil Protein Index Low	• Add N-rich organic matter (low C:N source like manure, high N well-finished compost) • Incorporate young, green, cover crop biomass • Plant legumes and grass-legume mixtures • Inoculate legume seed with Rhizobia & check for nodulation	• Reduce tillage • Rotate with forage legume sod crop • Cover crop and add fresh manure • Keep pH at 6.2-6.5 (helps N fixation) • Monitor C:N ratio of inputs
Soil Respiration Low	• Maintain plant cover throughout season • Add fresh organic materials • Add manure, green manure • Consider reducing biocide usage	• Reduce tillage/mechanical cultivation • Increase rotational diversity • Maintain plant cover throughout season • Cover crop with symbiotic host plants
Active Carbon Low	• Add fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Cover crop whenever possible

Management Suggestions for Chemical Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Soil pH Low	• Add lime or wood ash per soil test recommendations • Add calcium sulfate (gypsum) in addition to lime if aluminum is high • Use less ammonium or urea	• Test soil annually & add "maintenance" lime per soil test recommendations to keep pH in range • Raise organic matter to improve buffering capacity
Soil pH High	• Stop adding lime or wood ash • Add elemental sulfur per soil test recommendations	• Test soil annually • Use higher % ammonium or urea
Extractable Phosphorus Low	• Add P amendments per soil test recommendations • Use cover crops to recycle fixed P • Adjust pH to 6.2-6.5 to free up fixed P	• Promote mycorrhizal populations • Maintain a pH of 6.2-6.5 • Use cover crops to recycle fixed P
Extractable Phosphorus High	• Stop adding manure and compost • Choose low or no-P fertilizer blend • Apply only 20 lbs/ac starter P if needed • Apply P at or below crop removal rates	• Use cover crops that accumulate P and export to low P fields or offsite • Consider low P rations for livestock • Consider phytase for non-ruminants
Extractable Potassium Low	• Add wood ash, fertilizer, manure, or compost per soil test recommendations • Use cover crops to recycle K • Choose a high K fertilizer blend	• Use cover crops to recycle K • Add "maintenance" K per soil recommendations each year to keep K consistently available
Minor Elements Low	• Add chelated micros per soil test recommendations • Use cover crops to recycle micronutrients • Do not exceed pH 6.5 for most crops	• Promote mycorrhizal populations • Improve organic matter • Decrease soil P (binds micros)
Minor Elements High	• Raise pH to 6.2-6.5 (for all high micros except Molybdenum) • Do not use fertilizers with micronutrients	• Maintain a pH of 6.2-6.5 • Monitor irrigation/improve drainage • Improve soil calcium levels

School of Integrative Plant Science, Soil and Crop Sciences Section, G01 Bradfield Hall, 306 Tower Road, Cornell University, Ithaca, NY 14853, email: soilhealth@cornell.edu

College of Agriculture and Life Sciences, Cornell University Developed in partnership with Cornell Soil Health, Farmier, and GreenStart.

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:		Sample ID:	VVV1659
Bora Cetin		Field ID:	Yard-Waste Compost
centinbor@msu.edu		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	<u>Predicted</u> 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

Measured Soil Health Indicators

The Cornell Soil Health Test measures several indicators of soil physical, biological and chemical health. These are listed on the left side of the report summary, on the first page. The "value" column shows each result as a value, measured in the laboratory or in the field, in units of measure as described in the indicator summaries below. The "rating" column interprets that measured value on a scale of 0 to 100, where higher scores are better. Ratings in red are particularly important to take note of, but any in yellow, particularly those that are close to a rating of 30 are also important in addressing soil health problems.

- **A rating below 20 indicates *Very Low (constraining)* functioning and is color-coded red.** This indicates a problem that is likely limiting yields, crop quality, and long-term sustainability of the agroecosystem. In several cases this indicates risks of environmental loss as well. The "constraint" column provides a short list of soil processes that are not functioning optimally when an indicator rating is red. It is particularly important to take advantage of any opportunities to improve management that will address these constraints.

- **A rating between 20 and 40 indicates *Low* functioning and is color-coded orange.** This indicates that a soil process is functioning somewhat poorly and addressing this should be considered in the field management plan. The Management Suggestions Table at the end of the Soil Health Assessment Report provides linkages to field management practices that are useful in addressing each soil indicator process.

- **A rating between 40 and 60 indicates *Medium* functioning and is color-coded yellow.** This indicates that soil health could be better, and yield and sustainability could decrease over time if this is not addressed. This is especially so if the condition is being caused, or not being alleviated, by current management. Pay attention particularly to those indicators rated in yellow and close to 40.

- **A rating between 60 and 80 indicates *High* functioning and is color-coded light green.** This indicates that this soil process is functioning at a non-limiting level. Field soil management approaches should be maintained at the current intensity or improved.

- **A rating of 80 or greater indicates *Very High* functioning and is color-coded dark green.** Past management has been effective at maintaining soil health. It can be useful to note which particular aspects of management have likely maintained soil health, so that such management can be continued. Note that soil health is often high, when first converting from a permanent sod or forest. In these situations, intensive management quickly damages soil health when it includes intensive tillage, low organic matter inputs, bare soils for significant parts of the year, or excessive traffic, especially during wet times.

- **The Overall Quality Score** at the bottom of the report is an average of all ratings and provides an indication of the soil's overall health status. However, the important part is to know which particular soil processes are constrained or suboptimal so that these issues can be addressed through appropriate management. Therefore, the ratings for each indicator are more important information.

The Indicators measured in the Cornell Soil Health Assessment are important soil properties and characteristics in themselves, but also are representative of key soil processes, necessary for the proper functioning of the soil. The following is a summary of the indicators measured, what each of these indicates about your soil's health status, and what may influence the relevant properties and processes described.

A Management Suggestions Table follows, at the end of the report, with short and long term suggestions for addressing constraints or maintaining a well-functioning system. This table will indicate constraints identified in this assessment for your soil sample by the same yellow and red color coding described above. Please also find further useful information by following the links to relevant publications and web resources that follow this section.

Texture is an inherent property of soil, meaning that it is rarely changed by management. It is thus not a soil health indicator per se, but is helpful both in interpreting the measured values of indicators (see the Cornell Soil Health Assessment Training Manual), and for deciding on appropriate management strategies that will work for that soil.

Your soil's measured textural class and composition: clay Sand: 41% Silt: 15% Clay: 43%

Predicted Available Water Capacity (AWC) is not a directly measured soil property but is modeled from a suite of measured soil health indicators including the percent sand, silt, clay and organic matter. By using a decision tree approach, the developed Random Forest model can predict the laboratory measured AWC value with no more error than that encountered in the raw laboratory analysis. Details of this modeling effort can be found in our Soil Health Management Series Fact Sheet Number 19-05b.

The Soil Health Lab continues to offer the laboratory measured AWC test as an add-on to the soil health package analyses.

The Predicted AWC value is presented as grams of water per gram of soil. This value is scored against an observed distribution in regional soils with similar texture. A physical soil characteristic, AWC is an indicator of the amount of plant-available water the soil can store, and therefore how crops will fare in droughty conditions. Soils with lower storage capacity will cause greater risk of drought stress. AWC is generally lower when total organic matter and/or aggregation is low. It can be improved by reducing tillage, long-term cover cropping, and adding large amounts of well-decomposed organic matter such as compost. Coarse textured (sandy) soils inherently store less water than finer textured soils, so that managing for relatively high-water storage capacity is particularly important in coarse textured soils. While the textural effect cannot be influenced by management, management decisions can be in part based on an understanding of inherent soil characteristics.

Your Predicted Available Water Capacity value is **0.25 g/g**, corresponding with a score of **90**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this**

condition, as it currently indicates ideal soil functioning. Please refer to the management suggestions table at the end of this document.

Aggregate Stability is a measure of how well soil aggregates or crumbs hold together under rainfall or other rapid wetting stresses. Measured by the fraction of dried aggregates that disintegrate under a controlled, simulated rainfall event similar in energy delivery to a hard spring rain, the value is presented as a percent, and scored against a distribution observed in regional soils with similar textural characteristics. A physical characteristic of soil, Aggregate Stability is a good indicator of soil biological and physical health. Good aggregate stability helps prevent crusting, runoff, and erosion, and facilitates aeration, infiltration, and water storage, along with improving seed germination and root and microbial health. Aggregate stability is influenced by microbial activity, as aggregates are largely held together by microbial colonies and exudates, and is impacted by management practices, particularly tillage, cover cropping, and fresh organic matter additions.

Your measured Aggregate Stability value is **79.2 %**, corresponding with a score of 99. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Organic Matter (OM) is a measure of the carbonaceous material in the soil that is biomass or biomass-derived. Measured by the mass lost on combustion of oven-dried soil, the value is presented as a percent of the total soil mass. This is scored against an observed distribution of OM in regional soils with similar texture. A soil characteristic that measures a physical substance of biological origin, OM is a key or central indicator of the physical, biological, and chemical health of the soil. OM content is an important influence on soil aggregate stabilization, water retention, nutrient cycling, and ion exchange capacity. Soils with low organic matter tend to require higher inputs, and be less resilient to drought and extreme rainfall. The retention and accumulation of OM is influenced by management practices such as tillage and cover cropping, as well as by microbial community growth. Intensive tillage and lack of organic matter biomass additions from various sources (amendments, residues, active crop or cover crop growth) will decrease organic matter content and overall soil health with time.

Total Carbon (Tot C) is an indicator for the OM in soil, with carbon comprising 48-58% of the total weight of OM. The Tot C analysis measures all of the carbon in a sample using complete oxidation of carbon to CO2 using high temperature combustion (1100C). The measured Tot C includes ***organic*** forms of carbon (Soil Organic Carbon SOC), comprised of available carbon as well as relatively inert carbon in stable organic materials. Carbon can also be found in ***inorganic*** form (Soil Inorganic Carbon SIC) as carbonate minerals such as calcium carbonate (lime).

Soil Organic Carbon (SOC) is equivalent to Tot C when there are no carbonate minerals. However, soils above pH 6.5 may contain high levels of carbonates. These carbonates are measured as SIC and subtracted from the Tot C: **SOC = Tot C - SIC**.

Total Nitrogen (Tot N) includes the organic (living and non-living) and inorganic (or mineral) forms of nitrogen. About half of the Tot N found in soil is in relatively stable organic compounds. Inorganic nitrogen is liberated from organic nitrogen sources in the soil, particularly proteins and amino acids through the action of soil microorganisms. Ammonium ($NH4+$) and nitrate ($NO3-$) are the inorganic forms of nitrogen found in soil that are plant available. The Tot N is determined following the combustion methodology known as DUMAS.

> **Your measured Organic Matter value** is **21.4 %**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document. The **SOC** level is **19.38%**, the **Tot C** level is **19.87%**, the **Tot N** level is **1.37%**.

Soil Proteins are the fraction of the soil organic matter that are present as proteins or protein-like substances. This represents the large pool of organically bound N in the SOM, which microbial activity can mineralize, and make available for plant uptake. Measured by extraction with a citrate buffer under high temperature and pressure (hence Autoclave Citrate Extractable, or ACE proteins), the value given is expressed in mg extracted per gram of soil. As the method used extracts only a readily extractable fraction of the total amount of soil proteins in the SOM, we present this value as an index rather than as an absolute quantity. A measure of a physical substance, protein content is an indicator of the biological and chemical health of the soil, and is very well associated with overall soil health status. Protein content, as organically bound N, influences the ability of the soil to make N available by mineralization, and has been associated with soil aggregation and water movement. Protein content can be influenced by biomass additions, the presence of roots and soil microbes, and tends to decrease with increasing soil disturbance such as tillage.

> **Your measured ACE Soil Protein Index value** is **33.6** , corresponding with a score of 99. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Soil Respiration is a measure of the metabolic activity of the soil microbial community. Measured by capturing and quantifying carbon dioxide (CO 2) produced by this activity, the value is expressed as total CO 2 released (in mg) per gram of soil over a 4 day incubation period. Respiration is scored against an observed distribution in regional soils, taking texture into account. A direct biological activity measurement, respiration is an indicator of the biological status of the soil community, integrating abundance and activity of microbial life. Soil biological activity accomplishes numerous important functions, such as cycling of nutrients into and out of soil OM pools, transformations of N between its several forms, and decomposition of incorporated residues. Soil biological activity influences key physical characteristics like OM accumulation, and aggregate formation and stabilization. Microbial activity is influenced by management practices such as tillage, cover cropping, manure or green manure incorporation, and biocide (pesticide, fungicide, herbicide) use.

> **Your measured Soil Respiration value** is **2.0 mg**, corresponding with a score of **99**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Active Carbon is a measure of the small portion of the organic matter that can serve as an easily available food source for soil microbes, thus helping maintain a healthy soil food web. Measured by potassium permanganate oxidation, the value is presented in parts per million (ppm), and scored against an observed distribution in regional soils with similar texture. While a measure of a class of physical substances, active carbon is a good leading indicator of biological soil health and tends to respond to changes in management earlier than total organic matter content, because when a large population of soil microbes is fed plentifully with enough organic matter over an extended period of time, well-decomposed organic matter builds up. A healthy and diverse microbial community is essential to maintain disease resistance, nutrient cycling, aggregation, and many other important functions. Intensive tillage and lack of organic matter additions from various sources (amendments, residues, active crop or cover crop growth) will decrease active carbon, and thus will over the longer term decrease total organic matter.

> **Your measured Active Carbon value** is **1427 ppm**, corresponding with a score of **99**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Soil pH is a measure of how acidic the soil is, which controls how available nutrients are to crops. A physico-chemical characteristic of soils, pH is an indicator of the chemical or nutrient status of the soil. Measured with an electrode in a 1:1 soil:water suspension, the value is presented in standard pH units, and scored using an optimality curve. Optimum pH is around 6.2-6.8 for most crops (exceptions include potatoes and blueberries, which grow best in more acidic soil – this is not accounted for in the report interpretation). If pH is too high, nutrients such as phosphorus, iron, manganese, copper and boron become unavailable to the crop. If pH is too low, calcium, magnesium, phosphorus, potassium and molybdenum become unavailable. Lack of nutrient availability will limit crop yields and quality. Aluminum toxicity can also be a concern in low pH soils, which can severely decrease root growth and yield, and in some cases lead to accumulation of aluminum and other metals in crop tissue. In general, as soil OM increases, crops can tolerate lower soil pH. Soil pH also influences the ability of certain pathogens to thrive, and of beneficial organisms to effectively colonize roots. Raising the pH through lime or wood ash applications, and organic matter additions, will help immobilize aluminum and heavy metals, and maintain proper nutrient availability.

Your measured Soil pH value is **7.3** , corresponding with a score of **98**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Extractable Phosphorus is a measure of phosphorus (P) availability to a crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm), and scored against an optimality curve for sufficiency or excess. P is an essential plant macronutrient, and its availability varies with soil pH and mineral composition. Low P values indicate poor P availability to plants, and excessively high P values indicates a risk of adverse environmental impact through runoff and contamination of surface waters. Most soils in the Northeast store unavailable P from the soil's mineral make up or from previously applied fertilizer or manure. This becomes more available to plants as soils warm up. Therefore, incorporating or banding 10-25 lbs/acre of soluble 'starter' P fertilizer at planting can be useful even when soil levels are optimum. Some cover crops, such as buckwheat, are good at mining otherwise unavailable P so that it becomes more available to the following crop. When plants associate with mycorrhizal fungi, these can also help make P (and other nutrients and water) more available to the crop. P is an environmental contaminant and runoff of P into fresh surface water will cause damage through eutrophication, so over-application is strongly discouraged, especially close to surface water, on slopes, and on large scales.

Your measured Extractable Phosphorus value is **572.6 ppm**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that while the current management practices have created a non- limiting condition, careful management should be applied to manage excessively high levels.** Please refer to the management suggestions table at the end of this document.

Extractable Potassium is a measure of potassium (K) availability to the crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm), and scored against an optimality curve for sufficiency. K is an indicator of soil nutrient status, as it is an essential plant macronutrient. Plants with higher potassium tend to be more tolerant of frost and cold. Thus good potassium levels may help with season extension. While soil pH only marginally affects K availability, K is easily leached from sandy soils and is only weakly held by increased organic matter, so that applications of the amount removed by the specific crop being grown are generally necessary in such soils.

Your measured Extractable Potassium value is **4572.8 ppm**, corresponding with a score of **100**. This score is in the **Very High** range, relative to soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Minor Elements, also called secondary (calcium, magnesium and sulfur) and micro (iron, manganese, zinc, copper, boron, molybdenum, etc.) nutrients are essential plant nutrients taken up by plants in smaller quantities than the macro nutrients N, P and K. If any minor elements are deficient, this will decrease yield and crop quality, but toxicities can also occur when concentrations are too high. This assessment's minor elements rating indicates whether four measured micronutrients (magnesium, iron, manganese, and zinc) are deficient or excessive.

Micronutrient availability is strongly influenced by pH and organic matter. Low pH increases the availability of most micronutrients, whereas high pH increases the availability of molybdenum, magnesium and calcium. High OM and microbial activity tend to increase micronutrient availability. Note that this test does not measure all important micronutrients. Consider submitting a sample for a complete micronutrient analysis to find out the levels of the other micronutrients.

> **Your measured Minor Elements Rating** is **100**. This score is in the **Very High** range. Magnesium (2052.7 ppm) is sufficient, Iron (9.2 ppm) is sufficient, Manganese (48.8 ppm) is sufficient, Zinc (5.7 ppm) is sufficient. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates ideal soil functioning.** Please refer to the management suggestions table at the end of this document.

Overall Quality Score: an overall quality score is computed from the individual indicator scores. This score is further rated as follows: less than 20% is regarded as very low, 20-40% is low, 40-60% is medium, 60-80% is high, and greater than 80% is very high. The highest possible quality score is 100 and the least score is 0, thus it is a relative overall soil health status indicator. However, of greater importance than a single overall metric is identification of constrained or suboptimally functioning soil processes, so that these issues can be addressed through appropriate management. The overall soil quality score should be taken as a general summary rather than the main focus.

> **Your Overall Quality Score** is **99**, which is in the **Very High** range.

Management Suggestions for Physical and Biological Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Predicted Available Water Capacity Low	• Add stable organic materials, mulch • Add compost or biochar • Incorporate high biomass cover crop	• Reduce tillage • Rotate with sod crops • Incorporate high biomass cover crop
Aggregate Stability Low	• Incorporate fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage • Use a surface mulch • Rotate with sod crops and mycorrhizal hosts
Organic Matter Low	• Add stable organic materials, mulch • Add compost and biochar • Incorporate high biomass cover crop	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Incorporate high biomass cover crop
ACE Soil Protein Index Low	• Add N-rich organic matter (low C:N source like manure, high N well-finished compost) • Incorporate young, green, cover crop biomass • Plant legumes and grass-legume mixtures	• Reduce tillage • Rotate with forage legume sod crop • Cover crop and add fresh manure • Keep pH at 6.2-6.5 (helps N fixation) • Monitor C:N ratio of inputs
Soil Respiration Low	• Maintain plant cover throughout season • Add fresh organic materials • Add manure, green manure • Consider reducing biocide usage	• Reduce tillage/mechanical cultivation • Increase rotational diversity • Maintain plant cover throughout season • Cover crop with symbiotic host plants
Active Carbon Low	• Add fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Cover crop whenever possible

Management Suggestions for Chemical Constraints

Constraint	Short Term Management Suggestions	Long Term Management Suggestions
Soil pH Low	• Add lime or wood ash per soil test recommendations • Add calcium sulfate (gypsum) in addition to lime if aluminum is high • Use less ammonium or urea	• Test soil annually & add "maintenance" lime per soil test recommendations to keep pH in range • Raise organic matter to improve buffering capacity
Soil pH High	• Stop adding lime or wood ash • Add elemental sulfur per soil test recommendations	• Test soil annually • Use higher % ammonium or urea
Extractable Phosphorus Low	• Add P amendments per soil test recommendations • Use cover crops to recycle fixed P • Adjust pH to 6.2-6.5 to free up fixed P	• Promote mycorrhizal populations • Maintain a pH of 6.2-6.5 • Use cover crops to recycle fixed P
Extractable Phosphorus High	• Stop adding manure and compost • Choose low or no-P fertilizer blend • Apply only 20 lbs/ac starter P if needed • Apply P at or below crop removal rates	• Use cover crops that accumulate P and export to low P fields or offsite • Consider low P rations for livestock • Consider phytase for non-ruminants
Extractable Potassium Low	• Add wood ash, fertilizer, manure, or compost per soil test recommendations • Use cover crops to recycle K • Choose a high K fertilizer blend	• Use cover crops to recycle K • Add "maintenance" K per soil recommendations each year to keep K consistently available
Minor Elements Low	• Add chelated micros per soil test recommendations • Use cover crops to recycle micronutrients • Do not exceed pH 6.5 for most crops	• Promote mycorrhizal populations • Improve organic matter • Decrease soil P (binds micros)
Minor Elements High	• Raise pH to 6.2-6.5 (for all high micros except Molybdenum) • Do not use fertilizers with micronutrients	• Maintain a pH of 6.2-6.5 • Monitor irrigation/improve drainage • Improve soil calcium levels

School of Integrative Plant Science, Soil and Crop Sciences Section, G01 Bradfield Hall, 306 Tower Road, Cornell University, Ithaca, NY 14853, email: soilhealth@cornell.edu

College of Agriculture and Life Sciences, Cornell University Developed in partnership with Cornell Soil Health, Farmier, and GreenStart.

APPENDIX C
MINNESOTA NATIVE LANDSCAPE (MNL) USED IN THE FIELD STUDY

Seed name	lb/acre
Big Bluestem	0.84
Side-oats Grama	1.72
Prairie Brome	0.24
Canada Wild Rye	0.60
Slender Wheat Grass	0.72
Virginia Wild Rye	0.66
Switchgrass	0.42
Little Bluestem	2.16
Indian Grass	1.32
Rough Dropseed	0.30
Prairie Dropseed	0.02
Yarrow	0.01
Fragrant Giant Hyssop	0.02
Leadplant	0.14
Common Milkweed	0.09
Butterfly Milkweed	0.04
Canada Milk Vetch	0.21
White Prairie Clover	0.32
Purple Prairie Clover	0.48
Showy Tick-trefoil	0.35
Prairie Cinquefoil	0.03
Rattlesnake Master	0.12
Wild Licorice	0.03
Maximillian's Sunflower	0.07
Common Ox-eye	0.18
Meadow Blazing Star	0.09
Prairie Blazing Star	0.08
Wild Bergamot	0.05
Mountain Mint	0.01
Yellow Coneflower	0.10
Black-eyed Susan	0.16
Stiff Goldenrod	0.10
Showy Goldenrod	0.02
Smooth Blue Aster	0.03
New England Aster	0.04
Sky-blue Aster	0.04
Blue Vervain	0.05
Culver's Root	0.01
Heart-leaved Alexanders	0.01

Seed name	lb/acre
Golden Alexanders	0.12

APPENDIX D
COST EVALUATION SPREADSHEET

Purpose:

This tool is designed to estimate approximate cost of roadside vegetation applications (compost and proprietary amendments)

Input Section:

1) Select the type of the material used in roadside vegetation application by checking the corresponding checkbox.

2) Input the application area, material costs, excavation machinery and labor costs

<u>Application Area</u>

Length: Length of the area, in (ft) Width: Width

of the area, in (ft)

Thickness: Thickness of the area, in (inches) *<u>Material Cost</u>*

Compost: Amount of compost that will be used in roadside vegetation application, in (CY)

Proprietary Amendment: Amount of proprietary amendment that will be used in roadside vegetation application, in (Ibs)

Field: Area of field for seeding, in (acre)

Blanket: Amount of erosion control blanket that will be used in roadside vegetation application, in (roll)

<u>Excavation Machinery and Labor Costs</u>

Number of Excavator: Number of excavator/skid loader that will be used in roadside vegetation application, in (number)

Avg. miles to transport equipment and soils: Average miles to transport equipment and soils, in (miles) Number of

truck: Number of transportation truck to transport equipments and materials, in (number) Labor hour: Number

of hours for construction workers, in (number)

Labor worker: Number of construction workers during roadside vegatation application project, in (number)

Instructions:

1) Under the "INPUT" section, choose the roadside vegetation application type by checking the appropriate box.

2) Fill the roadside geometry in the application area.

3) Depending on the roadside vegetation application type (compost or proprietary amendment), Compost and proprietary amendment boxes should be filled. For example, if the user select Compost checkbox, Compost (CY) should be filled.

4) Fill the planned area of field (acre) for seeding and number of blanket (roll)

5) Fill number of excavator, average miles to transport equipment and soils, number of truck, labor hour and labor number.

6) Once preferred inputs are entered, click the "CALCULATE" button under "Quantity of Materials for Construction". The "OUTPUT" section will display the estimated amount of seed, blanket and soil volume.

7) Once preferred inputs are entered, click the "CALCULATE" button under the "Total Cost of Roadside Application". The "OUTPUT" section will display the estimated cost of roadside application.

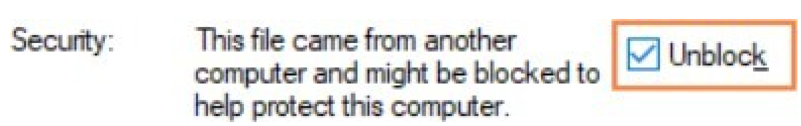
Output Section:

The tool outputs Quantity of Materials for Construction and Total Cost of Roadside Application ($) based on the entered application type, geometry and costs.

Notes for Excel Macros:

Option 1:

1) Fill in all required fields to enable calculation.
2) If calculations do not appear, ensure that Excel macros are enabled.
3) If a Security Warning about macros appears, follow these steps:
   a) Close the workbook.
   b) Right-click the file and select *Properties* from the menu.
   c) In the *Properties* dialog box, check "*Unblock*" and then click "OK".



<u>Option 2:</u>

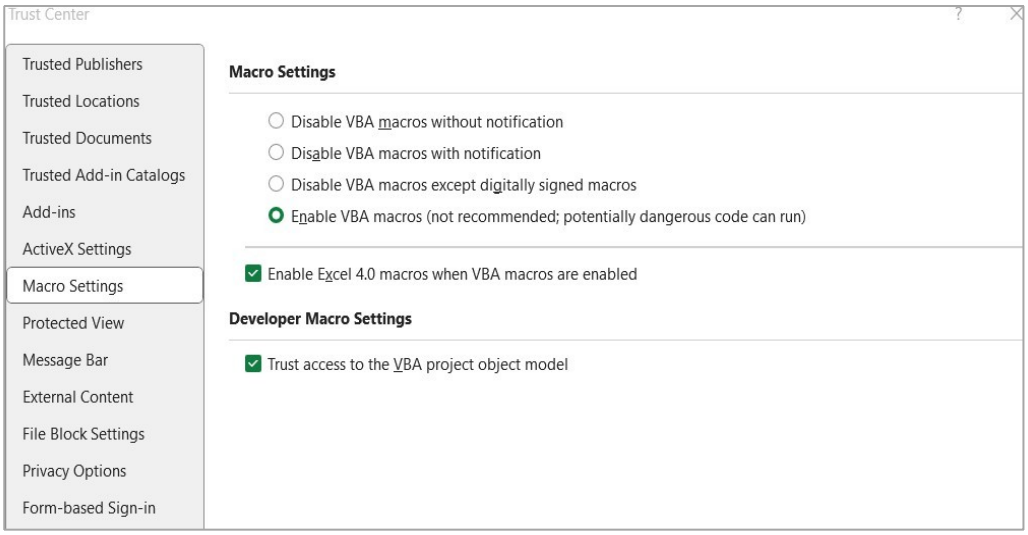
1) Open the workbook

2) Navigate to 'File' > 'Options' > 'Trust Center'.

3) Select Trust Center Settings

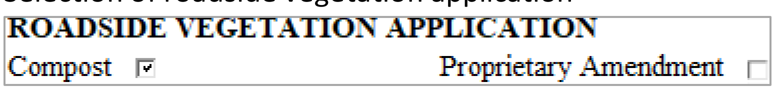
4) Click on 'Macro Settings' from the menu on the left.

5) Adjust the settings as shown below.

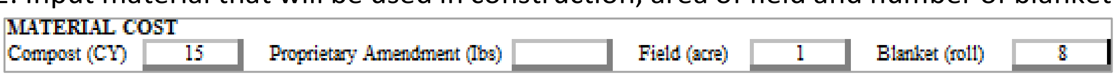


<u>Example for Compost Application</u>

Step 1: Selection of roadside vegetation application

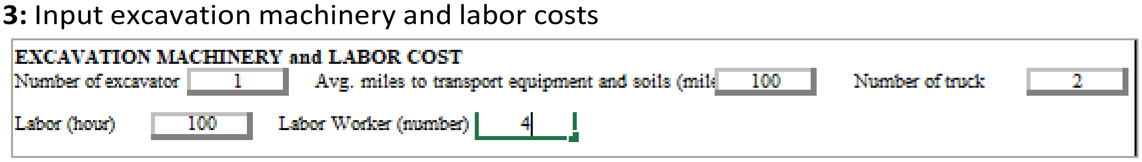


Step – 2: Input material that will be used in construction, area of field and number of blanket (roll)



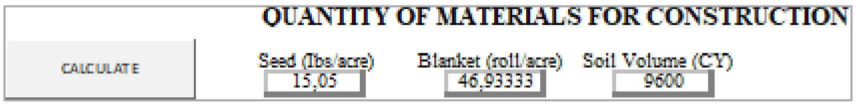
Note: If the user select compost as an roadside application, proprietary amendment cell should be blank.

Step – 3: Input excavation machinery and labor costs

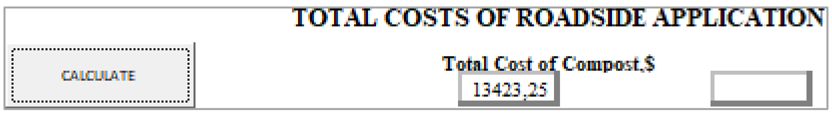


Note: Not all the cells have to be filled. The user can optionally leave the cell blank/empty depending on the costs and preference.

Step – 4: Output- First calculate button shows the quantity of materials for constructions.



Step – 5: Output- First calculate button shows the total cost of compost application on roadsides.



<u>**Important Note for the Cost Estimation**</u>

1) Material unit costs can change/fluctuate with time. Calculations based on the prices in late December 2024.

2) The user can update the material unit cost on "DATA spreadsheet".