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RESEARCH REPORT

SUSTAINABLE LANDSCAPING PRACTICE FOR ENHANCING VEGETATION ESTABLISHMENT

University of Maryland Baltimore County
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16. Abstract

Soil compaction can severely limit the success of vegetation establishment. Current grading and landscaping practices commonly produce compacted soils of varied textures and profiles within SHA medians and roadsides, resulting in limited capacity to support healthy vegetation or stormwater infiltration. This report reviews the available practices and procedures to improve soil structure that will help turf, meadow, and landscape plantings to thrive while reducing stormwater runoff. Modifications to standard recommended practices for final finish grading and final landscaping can avoid or mitigate soil compaction, and establish superior sustainable landscapes.

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Acronyms and Abbreviations

1:5 ww	Designates soluble salt analyte derived from 1:5 compost:water mixture on a weight-to-weight (ww) basis.
BD	Bulk Density
C:N	Carbon-to-nitrogen ratio. Used to characterize compost nutrient content.
DOT	Department of Transportation
FR	Forage Radish
GPS	Global Positioning System
GMC	Gravimetric Moisture Content
GLBD	Growth Limiting Bulk Density
in/hr	inches per hour. Unit used to report infiltration and standard deviation of measurements. E.g. 1.5 in/hr ± 0.1 indicates a mean infiltration rate of 1.5 inches per hour with a standard deviation of only 0.1 in/hr.
MPa	Metric unit of pressure. 1 MPa = 145.038 pounds per square inch (psi).
Mmhos/cm	millimhos per centimeter – a unit of electrical conductivity used in reporting salts
MS4	Municipal Separate Storm Sewer System
OF	Open Field
OM	Organic Matter
PT	Pre-Treatment
RB	Road Bed
SSC	Sand, Silt and Clay
SA	Staging Area
ST	Standard Turf
SHA	State Highway Administration
SS	Suburban Subsoiling
TMDL	Total Maximum Daily Load
TDR	Time Domain Reflectometry
WIP	Watershed Implementation Plan

Executive Summary

This research supports the integration of new practices and procedures to improve soil structure that will help turf, meadow, landscape and forest plantings to thrive. Cultivating deep permeable organic soil profiles by adapting current grading and land development practices, results in reduced life-cycle costs for green asset maintenance by establishing superior sustainable landscapes as standard endpoints of SHA's managed property.

The primary objectives of this research were to:

1. Demonstrate and evaluate innovative subsoiling, soil amendment, and vegetation choices to improve vegetation establishment and hydrologic function in the disturbed and compacted soils of SHA median and roadside rights-of-way.
2. Evaluate the use of SHA deer compost as a beneficial soil additive for landscaping improvement
3. Evaluate the effectiveness of alternative vegetation choices selected for deep rooting characteristics to maintain soil structure and health.
4. Develop and test revised grading and site preparation specifications to avoid and mitigate soil compaction during construction operations.

The project established experimental test plots in Taneytown Maryland, at which field-scale soil decompaction and amendment practices were evaluated alongside standard SHA practices for turf establishment. The Taneytown site is heavily compacted in the old MD 853 roadbed, and has been identified for a future afforestation project by SHA. The site is representative of many SHA decommissioned field offices and staging areas that may require soil remediation. Replicate treatments with suburban subsoiling (the combination of deep soil ripping and compost amendment) were compared to standard SHA turf establishment. Replicate plots were also treated by planting forage radish to explore the feasibility of bio-drilling to loosen and improve compacted soils on the site. Plots were prepared and planted in fall 2014 and again in summer of 2015. Soil characteristics including texture, bulk density, organic matter, soil strength as measured with a cone penetrometer, and infiltration capacity, were evaluated both prior to treatment and after treatment and vegetative stabilization. The results demonstrated significant improvements to the compacted soils on the project site, resulting in more successful turf establishment, and dramatic increases in site infiltration.

Overall, the project found:

1. **Results demonstrate the superior persistent enhancement of soil properties, vegetation success and increased infiltration from suburban subsoiling.**

Mean infiltration rates in the subsoiled plots were two orders of magnitude greater than infiltration rates of either the pre-treatment soil conditions or the plots that were planted with standard SHA vegetation specifications. Suburban subsoiling created a deep reservoir of plant available nutrients and increased plant available water; this is expected to support long term vegetation success. The results of this project demonstrate significant benefits from incorporating suburban subsoiling to mitigate compacted soils on SHA projects.

2. **SHA deer compost proved to be an effective source of organic matter as compost amendment.**

The very mature compost had lower organic matter content than mature Leafgro compost and a low carbon-to-nitrogen (C:N) ratio that should not limit plant available nitrogen. The mature deer compost used in this project provided stable soil carbon with nutrients overwhelmingly delivered in organic forms, minimizing the risk of nutrient losses or leaching when properly applied and soil-incorporated.

3. **The success of radish plantings demonstrated the efficacy and success of seed-drillings as a minimally disruptive method to establish forage radish on SHA property.**

The significant radish development on plots with successful germination demonstrated the potential for biodrilling as a low-impact multi-year strategy to mitigate compaction on similar SHA property. Further research is warranted to (a) identify the compaction limits for biodrilling success; (b) improve the germination reliability for seed-drilled radish; and (c) evaluate the cumulative effects of multi-year seed-drilled radish treatments.

4. **The project recommended an "outcome-based" approach to managing grading and compaction on every SHA project by defining distinct zones prioritized by expected outcomes for (a) vegetation success; (b) hydrologic services; and (c) stability. Incorporating outcome-based recommendations from initial site design through construction, inspection, and long-term maintenance, provides a consistent framework to match grading, site preparation, stabilization, maintenance practices, and equipment choices, to site-specific soil and field conditions.**

Designating goals and services expected from every distinct sub-area in every project footprint provides a life-cycle framework for managing soil compaction on SHA sites. The extended literature review in Appendix A provides detailed information regarding revised grading and site preparation specifications to avoid and mitigate soil compaction during construction operations including:

- The outcome-based framework for site design and construction operations to achieve desired outcomes across the site
- Improved practices for topsoil placement
- Identifying vehicle and soil characteristics to avoid undesired compaction during construction, as well as standard landscaping, seeding and mowing operations.
- Identifying vehicle and soil characteristics to maximize the effectiveness of decompaction activities
- Target densities and soil moisture conditions to maximize hydrologic function and vegetative success without compromising soil stability
- Decompaction techniques combined with aggressive compost amendment to achieve a sustainable and highly functional soil profile

Beyond the primary goals for the research, the project undertook an extensive literature review that will be published as an internal reference document for SHA. The extended literature review included a more detailed examination of (a) measures of soil health and their applicability for MD SHA (b) mechanisms and criteria for soil compaction; and (c) a more detailed review of the relationship between equipment operating characteristics, soil properties and compaction vulnerability. It led to a functional synthesis for SHA purposes (including specific operational guidance for SHA New Holland mowing tractors) to indicate conditions with excessive compaction risks. It also led to a framework for recommended practices on all SHA projects, in which the total site footprint is managed for multiple objectives, balancing functional stability, vegetative success and hydrologic services.

The research supports a modification of SHA's site design and planting procedures to prioritize stability, hydrologic services, and vegetative success for each distinct sub-area of every SHA project footprint and land-holding. The pragmatic priorities set among these potentially competing goals provides a consistent framework to align means and methods, equipment choices, and specifications with expected outcomes, to enhance vegetative success and environmental services with sustainable landscaping practices on every SHA project.

1. Introduction

Practices that establish and maintain healthy soil profiles offer a cost-effective strategy for improving the sustainability of highway landscape plantings. Current grading and landscaping practices commonly produce compacted soils of varied textures and profiles within SHA medians and roadsides, resulting in limited capacity to support healthy vegetation or stormwater infiltration. Practices that improve soil physical structure including tilling, subsoiling, and soil amendments have been shown to dramatically improve soil health and vegetation establishment, as well as reducing stormwater runoff with its associated loads of nutrients and sediment.

1.1 Background and Motivation

Compacted and highly disturbed urban soils are a ubiquitous feature of modern constructed landscapes. The standard practice of compacting and topsoiling soils associated with mass grading results in a "pervious" landscape with impaired infiltration capacity that constrains plant root growth, reduces soil water holding capacity, and limits the reservoir of plant-available nutrients in the root zone. The lost hydrologic function of the pervious landscape can be a significant source of stormwater runoff, nutrients, and sediment into the streams and tributaries of the Chesapeake Bay. Soil decompaction combined with aggressive organic compost amendment has proven effective for renovating compacted soils, restoring hydrologic function, and developing deeper rooted vigorous drought resistant vegetation in healthy dynamic soils. When properly planned and efficiently staged, this superior sustainable landscaping practice can be achieved cost-effectively through minor modifications to standard grading and landscaping practices. Compost incorporation practices can utilize SHA supplies of deer compost, providing a low cost benefit to soils as part of sustainable landscape operations.

The Maryland State Highway Administration (SHA) is a major land manager with a significant role to play in the Chesapeake Bay Total Maximum Daily Load (TMDL) and local watershed implementation plans (WIP). Medians, rights-of-way, and other property managed by SHA present a rich opportunity to improve stormwater services and the health, vigor, and successful establishment of vegetation on SHA-managed lands. SHA Business plan objectives explicitly framed the goal to ***"Annually improve/ maintain 86% of the state highway network in overall preferred condition."***

There is a growing recognition of the need for improved hydrologic and ecologic function from green landscapes (Chen et al., 2014; Hanks and Lewandowski, 2003; Haynes et al., 2013; Huinink, 1998; Jim, 1998; Olson et al., 2013). Low Impact Development (LID) practices provide improved hydrologic services, reducing runoff and pollutant loads from post-development landscapes. Avoiding or mitigating unnecessary soil compaction, reducing runoff, and restoring organic matter in a healthy soil profile represent broadly applicable core practices to cultivate sustainable multifunctional landscapes (Hanks and Lewandowski, 2003). Landscaping practices are evolving from simple turfgrass establishment to long-term establishment of sustainable healthy ecosystems. In the Chesapeake Bay region in particular, MS4 and TMDL requirements for stormwater motivate improved soil management to enhance hydrologic and ecological services.

This research supports the integration of new practices and procedures to establish healthy sustainable soil profiles that will help turf, meadow, and landscape plantings to thrive. Adapting current grading and land development practices that cultivate deep permeable organic soil profiles results in reduced life-cycle costs for green asset maintenance by establishing superior sustainable landscapes as standard endpoints of SHA's managed property.

1.2 Objectives

The primary objectives of this research were to:

1. Demonstrate and evaluate innovative subsoiling, soil amendment, and vegetation choices to improve vegetation establishment and improve hydrologic function in the disturbed and compacted soils of SHA medians and roadside rights-of-way.
2. Develop and test revised grading and site preparation specifications to avoid and mitigate soil compaction during construction operations.
3. Evaluate the effectiveness of alternative vegetation choices selected for deep rooting characteristics to maintain soil structure and health.
4. Evaluate the use of SHA deer compost as a beneficial soil additive for landscaping improvement

Chapter 2 reviews the most relevant literature on soil compaction and remediation that informed the experimental design, installation, and monitoring of soil plots at an SHA site in Taneytown, MD. Chapter 3 describes the study site and methods used to characterize and remediate the site. Chapter 4 reports results from experimental test plots at the Taneytown, MD study site. Chapter 5 discusses the results and their implications, and introduces modified practices that could be integrated into standard SHA operations to improve vegetation success and reduce stormwater runoff, with conclusions summarized in Chapter 6.

Appendix A contains an extended literature review on the causes and effects of soil compaction, compaction remediation techniques, as well as detailed derivation and supporting information for the modified practices recommended to improve the long-term management of soil compaction for vegetation success and stormwater management on SHA property.

2. Literature Review

2.1 Effects of Compaction

Soil compaction negatively affects the growth and long term success of vegetation. Root growth is limited by mechanical resistance in dense soil; when pore space is inadequate, roots must exert enough force to displace soil particles and create a channel for growth (Tracy et al., 2011). Increased mechanical resistance to root growth results in stiffened cell walls (Pritchard, 1994) and reduced osmotic potential (Bengough et al., 1997). As a result, roots become less effective at capturing water retained at high tension. Most crops and trees show reduced root growth and survival in response to increased mechanical impedance from soil compaction (Benigno et al., 2012; Gebauer et al., 2011; Olarieta et al., 2012; Sarquis et al., 1991; Valentine et al., 2012; Whalley et al., 1999).

Compaction affects the pore size distribution and the arrangement and continuity of soil pores (Kuncoro et al., 2014), distorting and reducing the connectivity of the macropore network (Schwen et al., 2011). Decreasing the mean pore size reduces plant available water (Blanco-Canqui et al., 2010). Changes to pore organization have a profound effect on hydraulic conductivity and gas transport and exchange (Berisso et al., 2013). Compaction has been shown to decrease hydraulic conductivity in all soil textures (Alaoui et al., 2011) around the world (Gebhardt et al., 2009; Gregory et al., 2006; Zhang et al., 2006). Heavy soil compaction can reduce oxygen diffusion by 70% (Czyz, 2004). The combination of decreased oxygen diffusion and reduced drainage can severely limit oxygen availability in compacted soils (Bassett et al., 2005). Root growth is, in turn, severely restricted by low oxygen supply (Leonard and Pinckard, 1946) and root elongation is highly sensitive to air-filled porosity (Voorhees et al., 1975). Reduction of pore space and gas exchange processes negatively affect the health and growth of roots, plants and soil biota.

Stifled root growth and reduced gas exchange reduce plants' ability to uptake nutrients (Arvidsson, 1999), whether present in organic form or as inorganic fertilizer (Jordan et al., 2003). The combination of inhibited root growth and reduced water and nutrient uptake limits plant growth (Masle and Passioura, 1987), directly limiting vegetation success. Turf, trees and crops are all negatively affected by soil compaction (Carrow, 1980; Corns, 1988; Day and Bassuk, 1994; Defossez et al., 2003; Hakansson et al., 1987; Ishaq et al., 2001; Jordan et al., 2003; Olarieta et al., 2012; Oussible et al., 1992; Raper, 2005a; Voorhees et al., 1989; Watson and Kelsey, 2006).

2.2 Sources of Compaction

Traditional construction and land development practices purposefully compact the soil to achieve specific goals. Soil is not compacted to increase density per se, but rather to increase soil strength and reduce compressibility, erodibility, settling, and shrink-swell potential (Gray, 2002;

Mohammed et al., 2010). Soil compaction in construction is commonly referred to as soil improvement (Mohammed et al., 2010; Tarawneh and Matraji, 2014; Vukadin, 2013). Stable soils are required for the preparation of roadbeds and building foundations.

In practice, compaction is not always limited to load-bearing areas of a site. The wholesale removal of topsoil and mass grading across the entire site footprint is a common construction practice. Vehicle traffic during construction can result in significant unintended soil compaction as evidenced by uniformly high soil densities across sites (Randrup and Dralle, 1997). Operating construction vehicles on wet soils can significantly increase the risk of unintended compaction (Wortmann and Jasa, 2003). In modern development, the cost effective practice of extensive clearing and mass grading over an entire site frequently results in soil compaction, by design (Friedman et al., 2001).

2.3 Managing Soil Compaction

2.3.1 Vegetation and State Transportation Agencies

Vegetative establishment is often difficult on disturbed compacted soils (Loschinkohl and Boehm, 2001; Shuster et al., 2014). Although rapid establishment of turf for erosion control is possible on compacted soil, poor vegetation survival may result and represents an ongoing concern for SHA. Compacted soils restrict and constrain root growth and tree survival in reforestation efforts (Löf et al., 2012), so effectively managing soil compaction is critical to ensure success of SHA Reforestation and Planting Programs[1]

Several other state departments of transportation (DOTs) have made efforts to remediate and manage soil compaction to balance competing goals for soil stability, vegetation success, and hydrologic function. The Minnesota DOT experimented with soil decompaction at construction sites and rights-of-way to improve infiltration (Chaplin, 2008). They developed a cost effective subsoiling procedure (<35$/acre) that resulted in enhanced vegetation establishment on previously compacted rights-of-way. The New York State Department of Environmental Conservation has developed subsoiling recommendations for the restoration of hydrologic function and long term vegetation success in large-scale heavily compacted construction sites (Lacey, 2008).

The California Department of Tranportation[2] (Caltrans) and the US Army Ecosystem Management and Restoration Research Program[3] undertook long-term investigations to balance

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[1] Reforestation and Planting Programs http://www.roads.maryland.gov/Index.aspx?PageId=315

[2] California DOT Soils Research http://www.dot.ca.gov/hq/LandArch/16_la_design/research/soils.htm

[3] US Army EMRRP http://www.dot.ca.gov/hq/LandArch/16_la_design/guidance/ec_toolbox/earthwork/soil_compaction_goldsmith.pdf

stability with improved vegetation success and stormwater infiltration[4]. The Caltrans[5] suggests loosening compacted soils for 3:1 and flatter slopes to improve infiltration, rooting depth and long-term vegetation success. Compost incorporation has been demonstrated to improve vegetation in disturbed road cuts in California (Curtis and Claassen, 2009). Both the Texas[6] and Virginia[7] DOTs investigated using compost to improve roadside vegetation. Improved land management practices can improve vegetation success and increase hydrologic function in transportation rights-of-way.

2.3.2 Compaction Management Hierarchy

Compaction management can be thought of through the hierarchy of: (1) avoiding compaction, (2) limiting compaction when it does occur, and (3) mitigating compaction to restore vegetation success and hydrologic services.

Compaction can be avoided by designating distinct grading and construction zones based on expected final uses, and controlling traffic accordingly. Randrup and Dralle (1997) found severely compacted soils throughout construction sites (i.e. unintentionally compacted planting zones), regardless of the intended use of the landscape footprint, due to inadequate zoning and traffic control. Fencing can protect soil for future planting (Randrup, 1997). When topsoil is stripped and stockpiled, a topsoil placement technique adapted from mine reclamation and reforestation known as loose tipping can avoid the construction of compacted final finish grades. Loose tipping can be used to place any desired depth of topsoil while avoiding the compaction risk associated with conventional spreading and grading (Moffat and Bending, 2000).

Compaction can be limited during construction by matching soil density specifications to the desired outcomes. Non load-bearing earthen fills are commonly compacted to 90% proctor density (Gray, 2002). This degree of compaction can be problematic for plant growth. The Growth Limiting Bulk Density (GLBD) for a given soil texture is the soil density threshold associated with restricted root penetration and reduced plant growth (Daddow and Warrington, 1983). Goldsmith et al. (2001) found that compacting soils to 85% proctor density did not exceed the GLBD, providing the benefits of compaction for non-load bearing stability without jeopardizing the growth and success of vegetation.

In addition to managing the degree of compaction for vegetation success, the soil moisture content during compaction operations can be specified to maximize hydrologic function. Soil moisture content during compaction has a profound effect on the resulting engineering

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[4] California DOT: Treating Construction Soils to Infiltrate Stormwater
http://www.dot.ca.gov/hq/LandArch/16_la_design/research/docs/Hilltop_Treating_Const_Soils_03-2010.pdf

[5] California DOT Erosion Control Toolbox: Decompact Soil Surface
http://www.dot.ca.gov/hq/LandArch/16_la_design/guidance/ec_toolbox/earthwork/decompact_soil_surface.htm

[6] Water Retention Techniques for Vegetation Establishment in TXDOT West Texas Districts
http://d2dtl5nnlpfr0r.cloudfront.net/tti.tamu.edu/documents/0-5748-1.pdf

[7] Soil Amendments for Roadside Vegetation in Virginia
http://infohouse.p2ric.org/ref/11/10294.pdf

properties, especially hydraulic conductivity (Gray, 2002). Soils compacted under moisture conditions drier than the optimum moisture from the proctor test (hereafter referred to as "dry-side" moisture) retain more soil structure and interconnected pore space compared to soils compacted under wet-side conditions (Chapuis et al., 1989; Lambe, 1958). For soils of the same texture and density, these structural differences can lead to orders of magnitude differences in permeability; soils compacted on the dry-side will retain significantly greater hydrologic function (Di Benedetto et al., 2003; Elsbury et al., 1990). Explicit specifications of soil moisture conditions for compaction can optimize hydrologic function and vegetation success while satisfying densification needs for soil stability.

Compaction can be limited during standard landscaping and maintenance activities (e.g. tilling, planting, and mowing) by matching equipment to the soil. Simple rules of thumb for avoiding soil compaction are abundant: don't operate equipment on soils near field capacity, minimize axle load and repeated wheeling, and use low pressure radial tires (Duiker, 2004; Schjonning et al., 2012). Dry soils resist compaction more than wet soils (Blackwell, 1979; Hakansson et al., 1987; Hamza et al., 2011; Lamandé and Schjønning, 2011; Richard et al., 1999). Equipment choices that (1) reduce the load and (2) increase the tire contact area tend to reduce soil compaction from vehicle operation (Arvidsson and Keller, 2007). Contact area is greater for radial tires than bias ply tires (O'Sullivan et al., 1999), and increases with decreasing tire inflation pressure (Keller and Arvidsson, 2004). A site specific assessment of compaction risk for a given soil condition and vehicle using a cone penetrometer is presented by Fritton (2008).

When compacted field conditions already exist, or can't reasonably be avoided during construction activities, remediation techniques are available to restore the soil profile to a less compacted state that can support enhanced vegetation and provide restored hydrologic services.

2.4 Remediation Techniques

Among diverse professional communities spanning agriculture to mine reclamation, a wide range of mitigation techniques have been developed that can be productively adapted to soil decompaction for typical SHA projects and property. Different remediation techniques are appropriate depending on the degree of soil compaction, across a spectrum from minimal effort techniques like soil naturalization, through mechanical intervention and ultimately soil replacement.

Biological activity can improve the quality of soils as root growth and penetration fragments the soil, penetrating zones of failure and allowing roots to expand in massive structure-less soil. Along with soil ecosystem processes and bacterial and fungal activity, root growth can induce soil loosening and promote aggregate formation if the soil is not excessively compacted (Angers and Caron, 1998). Biological remediation involves the selective use of plants to alleviate compaction by exploiting the natural action of plant root growth to expand soil pores - a process referred to as "biological drilling" (Cresswell and Kirkegaard, 1995). Certain crop species with vigorous taproots create bio-pores and increase macroporosity at significantly higher rates than finer fibrous rooted crops (Bodner et al., 2014; Han et al., 2015). The bio-pores enable deeper improved root growth for the following crop. The presence of bio-pores can increase access to soil water and potential water uptake by crops planted in compacted soils, increasing drought resistance (Gaiser et al., 2012; Perkons et al., 2014). Forage radish is a particularly effective species at generating deep macropores through root growth (Chen and Weil, 2011), with the additional cover crop benefit of capturing residual nitrogen and preventing nutrient runoff (Dean and Weil, 2009). The taproot of forage radish can penetrate compacted soils with soil strength greater than 230 – 435 psi (2-3 MPa), which is generally considered root limiting for most crops (Chen and Weil, 2010).

There are, however, limits to the degree of compaction that can be effectively mitigated with biodrilling. Even deep-rooted, biodrilling plants can’t penetrate through highly compacted soils. When conditions do not allow for biological remediation, a form of active mechanical remediation is required.

Mechanical remediation refers to the use of powered equipment to physically disturb and decompact the soil. A variety of mechanical implements have been designed to alleviate subsoil compaction. These devices are generally tractor driven and designed to break up the subsoil below the depths affected by standard tillage practices - a process known as subsoiling (Nichols and Reaves, 1958). Deep-ripping blades are commonly used in subsoiling, and come in a variety of shank designs with conventional or winged tips (Raper, 2005b; Raper, 2005c; Raper and Schwab, 2009).

Subsoiling fractures massively compacted soils, creating a soil profile with deeper hydraulic drainage that generally improves infiltration in the treated soil (Hamza and Anderson, 2003; Schillinger and Wilkins, 1997; Steed et al., 1987). Subsoiling has been shown to decrease bulk density and increase soil moisture in agricultural experiments (Allen and Musick, 1992; Borghei et al., 2008; Evans et al., 1996) and on construction sites (Haynes et al., 2013). Ripping has also been shown to improve tree establishment on restored brownfield sites (Sinnett et al., 2008) and aids the survival and growth of trees on reclaimed mine lands (Fields-Johnson et al., 2014). Others (Moffat and Bending, 2000; Sinnett et al., 2006) have found ripping to only provide a temporary solution in highly compacted soils, as the soil fractures can collapse and return to a compacted state. Deep ripping should be used in conjunction with other practices to achieve a sustainable decompacted soil profile (Pagliai et al., 2004).

Combining mechanical decompaction with compost amendment can provide long-lasting enhancement of hydrologic and ecologic function of the treated soils. Improvements in plant growth and physical and chemical soil properties from decompaction and compost amendment were greater than those from tillage or surface applied compost alone (Curtis and Claassen, 2005; Loper et al., 2010; Nguyen et al., 2012). Compost incorporation can dramatically increase saturated hydraulic conductivity and porosity (Carter, 2007; Cogger, 2005; Curtis and Claassen, 2007; Logsdon and Malone, 2015; Olson et al., 2013). Compost incorporation, or amendment, increases soil organic matter, which can decrease bulk density, and increase water holding capacity and infiltration (Brown and Cotton, 2011; Khaleel et al., 1981; Pandey and Shukla, 2006).

Compost is organic matter that has been decomposed and digested over time by communities of fungi and bacteria to produce a stable organic-rich product that can be safely used for surface applications and soil incorporation. Compost can be created from a wide variety of organic source material. Woody waste and other plant material, manure from farm animals, municipal sewage sludge, treated sewage sludge called biosolids (Lu et al., 2012), paper mill sludge (Evanylo and Daniels, 1999), and even deer carcasses (Johnston, 2009) can be used as input for composting processes. These materials are generally very rich in nutrients and may be vectors for pathogens. Static composting of roadkill carcasses with wood chips is a low cost, low biosecurity risk technique to simultaneously dispose of roadkill while producing an effective soil amendment for highway right-of-way projects (Bonhotal et al., 2007).

The application rate and depth of incorporation for a compost amendment determine the ratio of soil-to-compost. Loschinkohl and Boehm (2001) amended the top 15cm of a disturbed urban soil with a 10% by volume addition of composted biosolids (a 9:1 soil-to-compost ratio) and observed the suppression of turfgrass diseases and improved vegetative growth. Greater depth and rate of amendment can provide additional benefits beyond turf grass health (Brown and Cotton, 2011).

Although findings vary, deep incorporation (at least 6 inches) with a 3:1 or 2:1 ratio of soil-to-compost (25% and 33% by volume, respectively) has been shown to effectively achieve sustainable benefits (Cogger, 2005; Curtis and Claassen, 2009). In temperate humid climates similar to Maryland, Cogger (2005) recommends a 2:1 ratio (33% by volume) to establish landscape beds and a reduced application of 4:1 (~20%) by volume for lawns - to establish a deep nutrient reservoir. An aggressive, one time compost amendment can jumpstart a deep, healthy, sustainable soil profile with improved hydrologic and ecological function (Larney and Angers, 2012). Compost amendment has been successfully utilized to improve soil properties and vegetation success in agriculture, urban and suburban landscaping, and reclamation of mining and forestry sites (Cogger, 2005; Evanylo et al., 2008; Shiralipour et al., 1992; Sinnett, 2008).

Compost amendment is most effectively achieved using surface tillage equipment, as opposed to deep tillage equipment like subsoilers. Rotary tillers can decompact and incorporate amendments into the surface soil, allowing for better root penetration and water movement (Loper et al., 2010). However, rotary tillers generally achieve relatively shallow tillage depths and tend to pulverize the soil, destroying existing soil structure, disrupting *in situ* soil organic matter and shallow soil ecosystems (Moore and De Ruiter, 2012), and increasing the risk of erosion (Cannell and Hawes, 1994).

Soil spading offers an incremental improvement to rotary tillage. Spading is beneficial for soil quality, as the practice maintains significant soil structure without pulverizing soil peds (Pagliai et al., 2004). Soil spading can readily provide soil decompaction to depths of up to 1.3 feet (0.4 meter) (Bailey et al., 2010; Pezzi, 2005) as clearly seen in cone index profiles (Cogger et al., 2007). Tracer experiments (Grundy et al., 1999; Juzwik et al., 1997) show that spading can incorporate surface applied amendments more uniformly and to a greater depth than rotary tillers. This uniform incorporation to significant depths makes spaders an ideal tool for restoring degraded sites through decompaction and compost amendment (Bainbridge et al., 1999).

The combination of soil ripping and compost amendment with a spader, a process we refer to as *suburban subsoiling*, was implemented at the SHA Project Site in Taneytown, MD. The following section describes the Taneytown site and research methods used in this project.

3. Methods

3.1 Site Description and History

The study site is located in the Mesozoic lowlands of the Piedmont plateau, along 3438 Francis Scott Key Highway (MD Route 194) in Taneytown, MD (39^o 40 ‘ 32.88” N., 77^o 9’ 23.76”W). The online soil survey map for Carroll County, MD characterizes the site as Bucks Silt Loam, a prime farmland soil with good drainage and depth to restrictive feature (bedrock) between 40 to 60 inches.

Approximately 50 years ago, Francis Scott Key Highway replaced old State Route 853, the remnant right-of-way of which can still be seen as the dirt road running parallel to the highway (Figure 1). The clearing between the old roadbed and SR194 was used as a field office and construction staging area for an SHA project in Taneytown, MD. The staging area had a gravel base and supported trailers and construction equipment. Based on historical aerial imagery, the field office and staging area were constructed between Sept 2007 and Oct 2008, and were removed between Nov 2011 and July 2012. The pavement appears to have been removed shortly before the offices were removed. After decommissioning and pavement removal, the site was seeded and allowed to be recolonized by volunteer native vegetation.

This site is an excellent candidate for research on soil compaction for SHA. The site is heavily compacted in the old MD 853 roadbed, and has been identified for a future afforestation project by SHA. The site typifies many SHA decommissioned field offices and staging areas that may require soil remediation. Among candidate field sites, the Taneytown site offered easy access without the need for traffic control that would have been required for alternate sites in active medians.

3.2 Soil Characterization

Throughout this project, soil was characterized by analyzing soil bulk density (BD), organic matter (OM), texture or particle size distribution as percentages of sand, silt and clay (SSC), infiltration, and soil strength - characterized by cone penetrometer measurements of soil cone index (CI) values.

Soil Core Analysis

Shallow soil cores (2-inch diameter, 4-inch depth) were collected and used to estimate bulk density, organic matter, and soil texture. Cores were collected with an AMS (American Falls, ID) split core sampling cup driven with a slide hammer. Approximately 0.25-1" of the top of the recovered core (containing surface vegetation, roots and thatch) was gently extruded in the field and removed before capping the 4" core for laboratory analysis. Each core was extruded and weighed in the lab before being oven dried overnight at 220° Fahrenheit (105° Centigrade), with bulk density computed from the oven dried weight. Following bulk density estimation, each soil core was gently ground in a mortar with a rubber tipped pestle and screened through a 0.0787 inch (2 millimeter) sieve. A subsample of approximately 0.0882 ounces (25 grams) of the ground core was used to estimate organic matter content, determined by the loss on ignition method at 840° F (450° C). A second 1.764 ounce (50 gram) subsample of the ground sieved core was used for texture analysis using the hydrometer method (Gee and Bauder, 1986).

Infiltration Testing

Infiltration was measured using the single ring falling head method (Elrick et al., 1995; Touma et al., 2007; Zeleke and Si, 2005) using 6 inch (15 centimeter) diameter rings driven to an approximate depth of 3 inches (7.5 centimeters). A small section of a 7 mil (0.178 mm) thick plastic drop cloth was gently hand placed to conform to the inner ring wall and the soil surface before a pre-measured volume of water was applied to achieve an average initial head (H_0) of either 1.0 inch or 1.5 inches at the start of each test. The plastic was then smoothly removed to rapidly establish a nearly instantaneous uniform initial ponded head on the soil with minimal soil disturbance, marking the start of the drawdown test at time $t = 0$.

Measured head (H_t) and cumulative test time (t) were recorded until the soil surface was no longer fully submerged (marking the end of uniformly ponded conditions). The initial volumetric soil moisture content θ_0 was estimated by time domain reflectometry (TDR) as the average of four soil moisture measurements made around the perimeter of the ring using a spectrum Field Scout model TDR-100 soil moisture meter with 3 inch TDR rods. Soil moisture at the end of the test was similarly recorded inside the ring, as an estimate of the field saturated moisture content θ_{fs}. The change in volumetric soil moisture during the test was estimated as $\Delta\theta = \theta_{fs} - \theta_0$. Field saturated hydraulic conductivity K_{fs} was estimated from the drawdown curve and field estimated $\Delta\theta$, using Reynolds's (2008) solution for a falling head ring infiltrometer.

Cone Index / Soil Strength

The heterogeneity of soil strength was characterized in the field using a Spectrum Field Scout model SC-900 logging cone penetrometer. Cone penetrometer profiles were geo-referenced using a Trimble model Geo XH global positioning system (GPS). The cone penetrometer profiles offer a detailed surrogate characterization of the spatial heterogeneity of compaction between plots and across the site.

3.3 Initial Site Assessment 2012

The pre-treatment site condition was evaluated through an initial site assessment in the summer of 2012. The initial site assessment combined with knowledge of the site's history, informed the development of a plot plan with replicated treatments delineated in both (1) the compacted roadbed (RB) left from the removal of old State Route 853; and (2) the staging area (SA) where construction equipment had been stored adjoining the temporary SHA construction office. Additional sampling was performed in the open field (OF) area that was not disturbed by the SHA construction office (Figure 1).

3.4 Plot Plan

Replicate plots were established for treatment with (1) standard SHA turf establishment as per SHA specification 705; (2) suburban subsoiling – consisting of deep ripping, compost amendment with SHA deer compost, and compost incorporation by soil spading – followed by standard SHA turf establishment as per SHA specification 705; and (3) seed drilling forage radish, to evaluate *Daikon* radish planting for decompaction by biodrilling. Two additional sets of plots were delineated in the staging area for future evaluation of alternate afforestation techniques. The plot layout established three replicates of standard and subsoiled turf plots and forage radish, in both the staging area and in the roadbed. Plot dimensions of 12 feet by 55 feet were selected to allow the use of "full size" field-scale tillage equipment that would typically be used by SHA contractors. Plots were marked and georeferenced in the field.

Replicates of the standard turf (ST), suburban subsoiling (SS), and forage radish (FR) plots were numbered as shown in Figure 1. Plots 1-9 are in the roadbed (RB), while plots 10-18 are in the staging area (SA). These abbreviations will be used to refer to treatments and locations throughout this report.

Figure 1 - Plot Design

3.5 Plot Installation and Sampling

Summer 2014 Planting

Vegetation on the site was mowed and spray-killed with glyphosate in the summer of 2014. Ripping and compost application were performed by SHA District 7 maintenance personnel, using a Class II Worksaver R-130 single shank ripping blade procured for use with SHA District 7 mowing tractors as part of this research, in September 2014. Spading was performed by Autrusa Enterprises using an Imants model 33SX spader operating from an Antonio Carraro hydrostatic tractor in September 2014.

Standard turf (ST) plots were seeded and mulched with straw in October 2014, consistent with SHA Specification 705. SHA contractors did not plant the suburban subsoiling (SS) or forage radish (FR) plots in fall 2014, although the spaded SS plots received straw mulching. Small test areas of radish were hand planted in plots 9 and 18 in early Fall 2014, to get a preliminary indication of likely radish growth in the untreated compacted soils.

Summer 2015 Sampling

The wet spring and early summer of 2015 supported vigorous weed growth on the site. Dense volunteer vegetation that developed through the spring and summer limited summer data collection to soil core sampling from the ST and SS plots. Summer 2015 soil cores were collected in July and analyzed for BD, OM, and SSC.

Summer 2015 Planting

Difficulties completing the planting plan in 2014 led to the development of a small procurement for planting and/or seeding all plots in the summer 2015. In early August 2015, the site (with the exception of the ST plots) was again sprayed with herbicide and mowed to eliminate the dense weed and volunteer vegetation that developed. The second planting consisted of seed drilling the FR plots; fall turf establishment consistent with standard SHA specifications on the SS plots using excelsior matting instead of straw mulch; and overseeding the ST plots that had been planted in the summer of 2014.

Fall 2015 Sampling

After the plots were planted in August 2015, turf was allowed to germinate and grow-in through the fall of 2015. Fall 2015 field work sampled the ST and SS plots with a set of cone penetrometer profiles on each of the turf plots, as well as paired ST and SS infiltration tests on both the roadbed and staging area plots. Cone penetrometer surveys were collected from each plot in October 2015. Infiltration tests were performed in November 2015.

4. Results

4.1 Initial Site Assessment

Compost Analysis

Composite samples of the SHA Deer Compost were sent to the Penn State Agricultural Analytical Services Lab (State College, PA) for analysis using US Compost Council methods. The deer compost had a dry weight organic matter content of 40% with a C:N ratio of 13.7. Nitrogen was overwhelmingly present in organic form with less than 0.0001% inorganic ammonium content. Compost bioassay using Marketmore 76 Cucumber seed achieved 100% germination and 100% vigor relative to the control, consistent with very mature compost. Respiration testing yielded 1.2 mg $\mathrm{CO}_{2\text{-C/g organic matter/day}}$ indicating very stable compost. Respiration is reported in units of milligrams CO_2 carbon off gassed per gram of organic matter per day.

Table 1 - Penn State Compost Analysis

Analyte	*Results (As Is)*	*Results (Dry Weight)*
pH	7.4	
Soluble Salts (1:5 ww)*	0.93 mmhos/cm*	
Solids	69.8%	
Moisture	30.2%	
Organic Matter	27.9%	40.0%
Total Nitrogen (N)	1.1%	1.6%
Organic Nitrogen	1.1%	1.6%
Ammonium N	< 3.5 mg/kg	< 5.0 mg/kg
Carbon C	15.4%	22.1%
C:N Ratio	13.70	0.14
Phosphorous	0.56%	0.80%
Potassium	0.32%	0.45%
Calcium	7.69%	11.01%
Magnesium	0.74%	1.06%
Particle Size (< 9.5 mm)	94.28%	

*See list of acronyms and abbreviations for explanation of units.

Infiltration Testing and Soil Core Analysis

Despite the order of magnitude differences in mean infiltration rates among the open field (0.907 in/hr ± 0.95), staging area (0.060 in/hr ± 0.04) and roadbed (0.027 in/hr ± 0.02), the differences were not statistically significant – attributable to the high variability of the open field infiltration rates.

Two bulk density cores were collected at each infiltration test, with additional soil core samples taken from the roadbed. Mean and standard deviation of bulk density (BD), organic matter (OM), gravimetric moisture content at the time of sampling (GMC), and texture from soil core analysis are reported in Table 2.

Table 2 - Initial Site Assessment Soil Properties

	BD (g/cc)	*OM (%)*	*GMC (%)*	*Sand (%)*	*Silt (%)*	*Clay (%)*
Open Field	1.26 ± 0.09 ^{a}	5.46 ± 1.70 ^{a}	13.1 ± 2.1 ^{a}	23.2 ± 6.6 ^{a}	63.0 ± 5.7 ^{a}	13.9 ± 2.3 ^{a}
Staging Area	1.44 ± 0.15 ^{b}	3.09 ± 0.54 ^{b}	7.1 ± 2.2 ^{b}	38.6 ± 9.5 ^{b}	47.1 ± 6.6 ^{b}	14.3 ± 3.8 ^{ab}
Roadbed	1.58 ± 0.11 ^{c}	3.01 ± 0.37 ^{b}	8.9 ± 3.0 ^{b}	38.1 ± 2.8 ^{b}	46.0 ± 2.1 ^{b}	15.9 ± 1.3 ^{b}

Different superscripts within each column indicate values that are significantly different

The roadbed had the highest mean BD consistent with residual load-bearing compaction established during original roadbed construction, with BD significantly higher than soils in the staging area (p = 0.01)[8]. The open field area that was clearly outside the immediate disturbance limits of the staging area, showed significantly higher OM, GMC and lower mean BD – underscoring the compacted state of the staging area after demobilization.

Differences between the open field and roadbed were statistically significant for BD, OM, GMC, sand, silt and clay percentages. Differences between the open field and staging area were statistically significant for BD, OM, GMC, sand and silt percentages. Differences between the staging area and roadbed were statistically significant for BD only.

The site assessment indicated that both the roadbed and the staging area consisted of soil with a significantly different texture than the open field area, suggesting the transport, grading, and compaction of material used to develop the finish grade in both areas. The bulk density clearly showed the legacy compaction of both the roadbed and staging area as well as the significantly higher residual compaction of the roadbed. These results were determinative in motivating a plot design with replicated treatments on both the roadbed and the staging area, to evaluate the effect of soil decompaction treatments on both compacted subareas. Plot layout geo-located all test plots, to ensure their location on compacted areas of the original roadbed and staging area.

4.2 Summer 2015 Sampling

Late fall 2014 ST planting had poor germination success with highly variable turf cover on both roadbed and staging area plots. Figure 2 shows the poor turf establishment as of March 2015, six months after initial planting.

Figure 2 - Poor turf cover on ST plots, March 2015

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[8] Denotes the level of statistical significance of the difference in the mean.

By the end of spring 2015, the only ST plot with acceptable cover was plot 2 in the roadbed, attributable to higher moisture from significant canopy cover shading on the plot. The condition of plot 2 in May 2015, eight months after planting, is shown in Figure 3.

Figure 3 - Turf cover for plot 2 (ST in roadbed), May 2015

High soil moisture from a wet winter and spring resulted in very aggressive volunteer vegetation growth on the site in 2015 – especially on the SS plots. The density of the volunteer vegetation (prior to spraying and mowing in the late summer of 2015) limited data collection to soil bulk density cores that were collected from all ST and SS plots (a total of 12 plots). Two cores were collected from each plot. Results are reported in Table 3. Data from the two treatment areas are compared as both **pooled** data (SA+RB) and separately for SA and RB areas. Plots receiving the SS treatment consistently showed lower bulk density and higher organic matter than ST plots for SA, RB, and pooled data.

Table 3 - Soil Core Analysis: Summer 2015

	BD (g/cc)	*OM (%)*	*Sand (%)*	*Silt (%)*	*Clay (%)*
Pooled SS	1.11 ± 0.21	6.40 ± 1.90	39.7 ± 1.7	44.4 ± 2.7	15.9 ± 1.2
Roadbed SS	1.24 ± 0.16	5.82 ± 0.84	40.1 ± 1.9	44.0 ± 2.9	15.9 ± 1.3
Staging Area SS	0.98 ± 0.17	6.99 ± 2.54	39.3 ± 1.6	44.8 ± 2.6	15.9 ± 1.1
Pooled ST	1.56 ± 0.11	3.50 ± 0.44	39.0 ± 4.0	44.2 ± 5.2	16.8 ± 2.5
Roadbed ST	1.63 ± 0.08	3.42 ± 0.42	40.2 ± 2.2	44.1 ± 1.2	15.7 ± 1.5
Staging Area ST	1.49 ± 0.10	3.58 ± 0.48	37.9 ± 5.3	44.3 ± 7.7	17.9 ± 3.0

Texture differences between SS and ST plots were not significant, indicating the compost amendment had a negligible effect on the soil particle size distribution. SS plots in the staging area had significantly lower bulk density than SS plots in the roadbed, indicating suburban subsoiling significantly improved, but did not completely mitigate the higher compaction of the roadbed soils. Organic matter differences between roadbed and staging area SS plots were not significantly different, indicating equally effective compost incorporation between the two test areas.

The pooled SS plots had significantly lower bulk density and higher organic matter than the pre-treatment (PT) plots and the ST plots; these differences remained significant within separated RB and SA areas.

The pooled ST plots had significantly higher organic matter ($p<0.007$) than the pooled PT plots. However, the difference between ST and PT organic matter was not significant when comparing individual areas of SA ($p>0.08$) or RB ($p>0.06$). We speculate that the wet conditions in the early spring and summer of 2015 may account for the slightly higher organic matter from root growth of the vigorous volunteer vegetation and weed growth observed on the plots during summer sampling.

Bulk density of the ST plots was not significantly different from the bulk density prior to treatment, showing how the successful establishment of turf cover with standard SHA specifications *did not reduce compaction* in either the roadbed or the staging area.

Box-and-whisker plots displaying all BD and OM data are shown in Figures 4 and 5 respectively. Box and whisker plots show median and interquartile range, with squares showing mean values. Whiskers are drawn at the maximum of the data or ± 1.5 times the interquartile range.

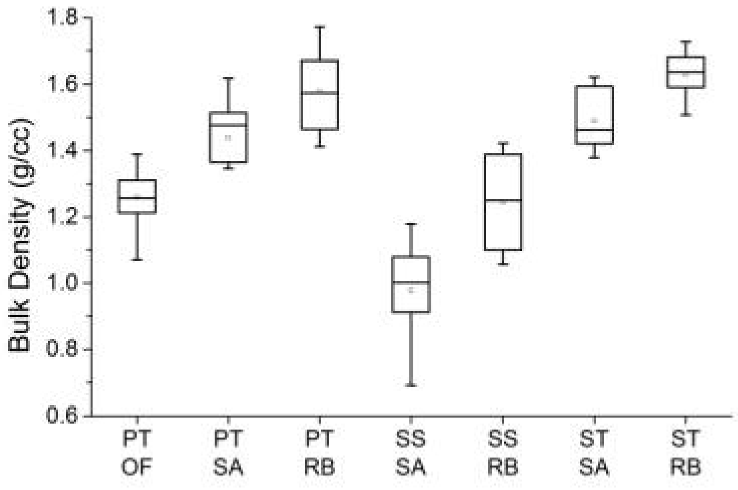


Figure 4 - Bulk Density of all samples. Site areas correspond to the open field (OF) staging area (SA) and roadbed (RB). Samples were taken pre-treatment (PT), following suburban subsoiling (SS), and following standard turf treatment (ST).

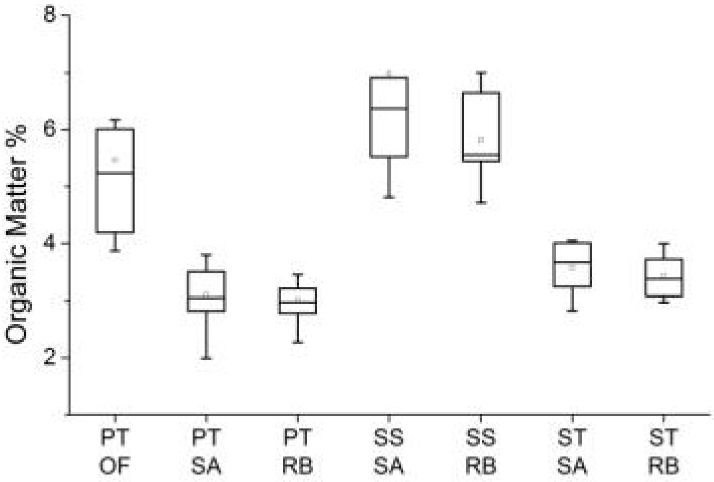


Figure 5 - Organic Matter for All Samples. Samples identified as in Figure 2.

4.3 Fall 2015 Sampling

Following planting and re-seeding in late summer 2015, cone penetrometer profiles were collected from each of the treated plots in October 2015. Profiles consist of cone index values (in units of PSI) at one inch depth increments. Between 18 and 22 cone penetrometer profiles were collected from each plot.   Mean cone index values by location and treatment were compared for each depth. Differences between the pooled ST and SS plots were statistically significant to a depth of at least 12 inches; these differences remained significant within separated RB and SA plots.

Medians and standard deviations of cone index at each depth were calculated for each treatment and location. Median cone index profiles for SS and ST treatments are shown from the staging area plots (Figure 4) and the roadbed plots (Figure 5). Critical root-limiting cone index thresholds of 200 PSI and 300 PSI are highlighted in both figures. Notice that median cone index for the SS plots remains below the 300 PSI threshold to depth in both the staging area and the roadbed, suggesting the significantly greater potential rooting depth created by suburban subsoiling.

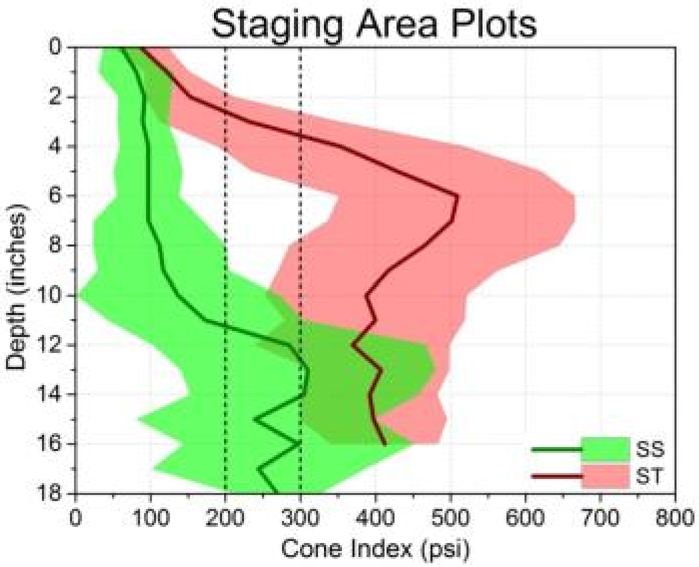


Figure 6 – Median Cone Index Profiles for Staging Area Plots

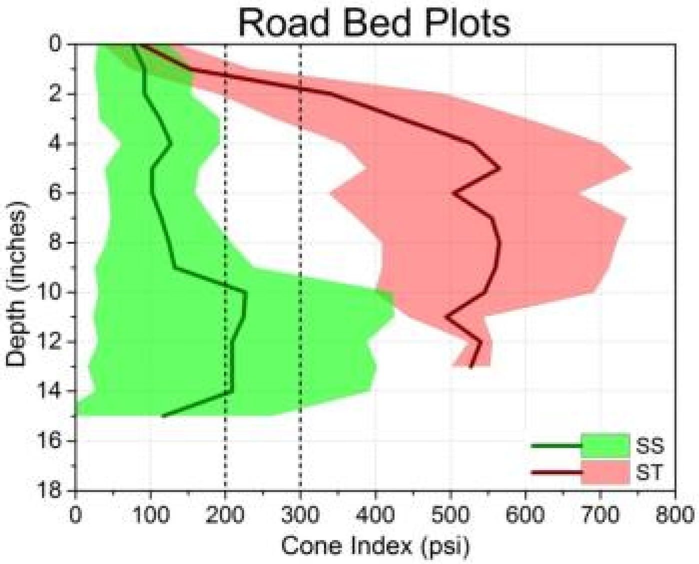


Figure 7 Median cone index profiles for roadbed plots

Infiltration testing was performed in November 2015. As a result of repeated vehicle traffic for multiple plot preparation and planting activities, the first SS plot on the roadbed (plot 1) became significantly more compacted than any of the other SS plots in either the roadbed or the staging area. Plot 1 received significantly more vehicle traffic than any other SS plot, often under high soil moisture conditions. Tire tracks were clearly visible on SS plot 1 in which soil was compacted to the point that it could not support vegetation. On reexamination, we found the cone index profiles on plot 1 showed significantly greater evidence of surface and subsoil compaction than any other SS plot. The median cone index on plot 1 now reaches the root impeding value of 200 psi at a depth of only 2 inches. For comparison, the median CI on Plot 8 (the last roadbed SS plot) does not reach 200 psi until a depth of nearly 11 inches. Figure 8 shows the differences in the median cone index profile between these two SS plots in the roadbed.

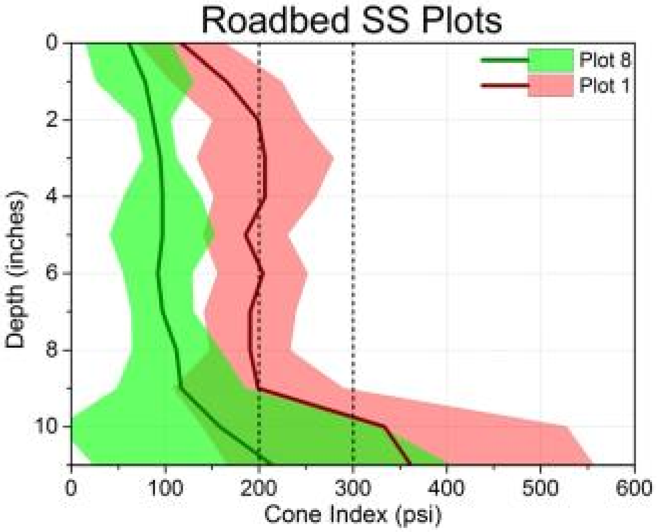


Figure 8 Comparing cone index for two SS roadbed plots

Plot 1 also has the highest mean bulk density of all the SS plots, and the lowest infiltration rate (1.86 in/hr.). When summarizing infiltration rates for roadbed SS plots, including plot 1 infiltration data raises the standard deviation of the mean infiltration rate from 0.071 in/hr to 3.286 in/hr. Collectively the plot 1 data combined with our understanding of the causes of these anomalies, led us to treat the unusually low infiltration rate on Plot 1 as an “outlier”. The low infiltration rate on plot 1 was therefore not included in the data comparisons described below.

Mean infiltration capacity of the pooled SS plots (8.70 in/hr. ± 1.014) is significantly greater than mean infiltration capacity of either the pooled ST (0.068 in/hr. ± 0.096) or pooled PT plots (0.042 in/hr. ± 0.035). These differences remain significant when analyzed separately for SA and RB areas.

SS plots in the staging area (9.467 in/hr. ± 0.306) had significantly higher infiltration rates than SS plots in the roadbed (7.55 in/hr. ± 0.071). Infiltration rates in the ST plots in the staging area (0.13 in/hr. ± 0.108) and ST plots in the roadbed (0.006 in/hr ± 0.004) were not significantly different ($p > 0.18$).

The dramatically higher mean infiltration capacity of the SS plots was significantly different from mean infiltration on the ST plots and followed the differences in cone index profiles and bulk density, as expected. Consistent with BD data, the infiltration capacity of the ST plots was not significantly higher than the pre-treatment infiltration rates, notwithstanding the acceptable (>95%) turf cover that was eventually established on most of the ST plots after overseeding.

The box and whisker plot in Figure 9 compares infiltration rates between the pre-treatment areas and the pooled treatment results. Note the inset plot that resolves the extremely low infiltration rates for PT and ST plots on a logarithmic scale. ST and SS treatments are not separated by location due to small sample size.

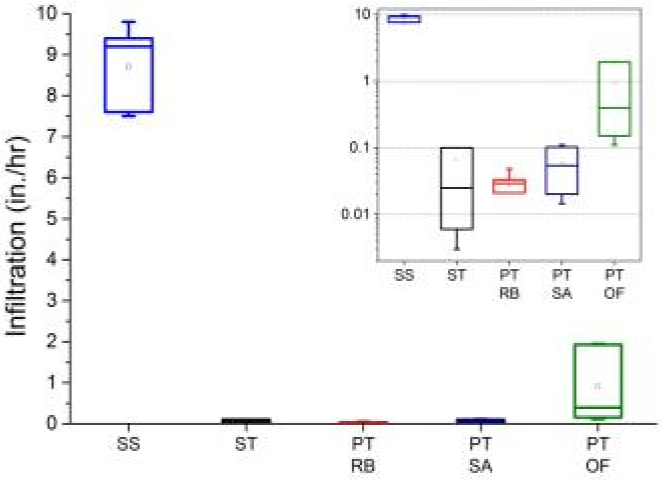


Figure 9 - Box and whisker plot of infiltration rate. Inset plot shows extremely low PT and ST infiltration rates on a logarithmic scale.

Radish Results

Relatively wet conditions in 2014 contributed to the successful germination of a small area of forage radish that was hand-planted in August 2014 in SA plot 9. These radishes reached maximum diameters of 1-inch with significant above ground crowns, as shown in figure 10. The small test area indicated that seed-drilled radish could realize significant beneficial growth without cultivation in the compacted soil of the staging area.

Figure 10 Forage Radish growth in hand planted area, November 2014

Replicate radish plots were planted with a seed drill in both SA and RB areas in late August 2015. Only one of the three forage radish roadbed plots (plot 6 in Figure 1) had significant radish germination, but growth was vigorous, with radishes reaching 1.5 inch diameters by December. Figure 11 shows a sample from the vigorous radish growth in plot 6, collected from within a 0.25 m^2 sampling frame. Frame dimensions are approximately 9.8 inches on all sides.

Figure 11 Forage Radish sampling in plot 6, December 2015

All three FR plots germinated in the staging area. However, the central plot (plot 15) showed significantly greater vigor, with radish diameters approaching 1.5 inches and significant above ground growth that noticeably lifted the radish crowns, as shown in Figure 12.

date.

Figure 12 Forage Radish growth in plot 15, December 2015

The research team noted a small localized area (~ 1 square yard) of staging area radish plot 12 near an animal burrow that showed vigorous radish growth – significantly greater than rest of the plot, as shown in Figure 13. It is speculated that nearby burrowing may have locally loosened soil to enable better rooting and more vigorous growth.

Figure 13 Forage Radish growth near animal burrow in plot 12, December 2015

Further evaluation of forage radish effectiveness was limited by the September 2015 planting date.

Turf Results

The ST plots planted in fall 2014 that germinated had an additional year of growth before all the ST plots were overseeded in fall 2015. After overseeding and late germination, ST cover appeared acceptable on all ST plots. Figure 14 shows typical turf cover on ST plots as of December 2015, twelve months after initial planting and four months after overseeding.

Figure 14 Turf cover on ST plots (plot 4 shown here), December 2015

Despite a wet spring and early summer, 2015 turf planting on the SS plots was delayed until late September. The combination of late planting, dry weather in late summer and early fall of 2015, and the use of excelsior matting on the subsoiled plots, appeared to delay full germination and grow-in on the SS plots. Nevertheless cover on the SS plots continued to grow-in through November field sampling, with increasingly vigorous dense cover developing. Figure 15 shows typical dense verdant turf cover growing through the excelsior matting on SS plots in December 2015, four months after planting.

Figure 15 Turf cover on SS plots (plot 17 shown here), December 2015

5. Discussion

5.1 Vegetation Success

Forage radish germination and growth was highly variable across the site. Roadbed plots (especially plot 3) showed surprisingly poor radish growth. Differences in vegetation success between the forage radish plots suggest residual soil compaction may be near the limits of compaction-limited radish growth, but available data are insufficient to evaluate this hypothesis. Nevertheless seed drilling was clearly successful in radish establishment without significant surface disturbance. The variable radish results suggest additional work beyond this project would usefully try to identify compaction limits for radish vegetation success, and evaluate over-year changes in soil characteristics as well as the cumulative effects of multiple years of radish plantings. Even the less vigorous 2015 radish plots had significant growth that will create substantial macropores in the compacted soil after frost-kill. These effects may have long-term afforestation benefits, and could suggest multi-year radish seed drilling as a minimally intrusive pre-treatment strategy (needing no sediment erosion control plan or permitting) for SHA afforestation projects on compacted soils.

5.2 Soil Organic Matter Persistence

After 2014, ripped and compost amended SS plots remained straw-mulched but unplanted, admitting volunteer vegetation and weed cover for nearly one year. Nevertheless there is no evidence of declining organic matter on the SS plots through the first year after treatment, consistent with the very mature state of the SHA deer compost. The low C:N ratio of the mature deer compost was not expected to significantly limit plant available N. The significant reservoir of organic nutrients from the deer compost represented a reliable source for the buildup of plant available nitrogen from mineralization in the first year following treatment. Despite its relatively low organic matter contents, the persistence and stability of the deer compost demonstrated its suitability for soil amendment on other SHA projects. The compost's maturity and lower organic content (~40%) are consistent with persistence of more recalcitrant carbon during the extended duration of the deer composting process.

5.3 Form and Function

Over-seeding established acceptable grass cover on all ST plots. Performance monitoring results showed that ***acceptable cover is not necessarily indicative of hydrologic function***. Performance monitoring data clearly showed the dramatic differences between SS and ST treatments. The box below highlights detailed results from two adjacent roadbed plots, plot 7 (ST) and plot 8 (SS).

Comparing Adjacent Roadbed Plots 7 (ST) and 8 (SS)

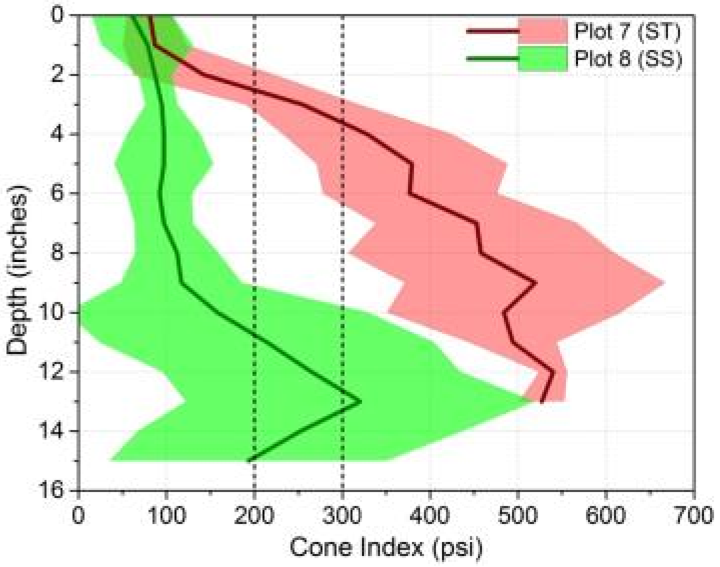
December 2015 inspection found acceptable turf coverage on both plots. The denser more verdant turf on SS Plot 8 was established without supplemental inputs (2nd year overseeding), which would not normally occur in SHA turf establishment.


Plot 7 (ST)


Plot 8 (SS)

Despite acceptable *cover* on both plots, the bulk density, organic matter, infiltration capacity and cone index profiles differ profoundly between the two treatments. The comparison underscores how SHA's current specification can achieve acceptable (>95%) turf cover without any improvement in densely compacted post-construction soils. The SS treatment produced superior turf without supplemental inputs (overseeding); an extraordinary increase in infiltration capacity; and a deep 10-12 inch rooting zone that should dramatically improve afforestation success. The chlorotic appearance of ST turf suggests nitrogen limitation. Verdant SS turf is consistent with mineralization of compost organic nutrients, maintaining plant available nitrogen.

	Plot 7 (ST)	**Plot 8 (SS)**
BD (g/cc)	1.59	1.13
OM (%)	3.5	5.2
Inf. (in./hr)	0.006	7.5



The comparison of both failed (2014) and successful (2015) ST turf establishment using standard SHA specifications highlighted the feasibility of establishing acceptable cover if SHA specs are *scrupulously* implemented - including monitoring germination success and following up with second-year overseeding or re-seeding as needed. This attention to overseeding may be atypical for most SHA projects. Results highlight that existing SHA turf grass specification 705 for turf establishment did eventually produce acceptable vegetative cover, but cannot be expected to significantly improve the permeability, potential rooting depth, or fertility of compacted soil profiles commonly produced by compaction and mass grading on SHA projects.

The stark contrast between the verdant SS turf and the chlorotic appearance of the ST turf raises substantive questions concerning the long-term vigor and viability of ST turf without ongoing supplemental nutrient inputs. We note standard practice in commercial landscaping includes routine annual application of supplemental fertilizer to turf grass. Such a practice would add significant annual costs to SHA vegetation maintenance, while significantly increasing the risk of nitrogen loading to the streams and tributaries of Chesapeake Bay. In contrast, the compost amended SS plots have a natural "slow release" source of plant available nitrogen, from slow steady mineralization of organic nutrients. Despite the acceptable cover initially established on both ST and SS plots, the denser verdant turf on SS plots can be expected to maintain denser cover, while adding new organic matter, organic nutrients and macropores to the soil profile as senescent roots and shoots slowly decay and are assimilated by soil ecosystem processes in the deeper amended SS soil profile. The greater erosion protection offered by denser SS turf, combined with the dramatic increase in infiltration and accompanying runoff reduction, substantially reduces nutrient and sediment loads to Chesapeake Bay by establishing superior sustainable landscaping.

Future tree-plantings on the undisturbed Taneytown site can be expected to suffer from the same compaction related constraints that limit tree survival on other compacted SHA sites unless additional aggressive soil decompaction practices are implemented. In contrast to the ST treatment, the SS plots showed dramatic persistent differences in soil bulk density, organic matter, penetrometer profiles, and infiltration. The acceptable cover on the SS plots was associated with much deeper rooting potential from the decompacted amended profile, and was achieved without the additional second year inputs of overseeding performed on the ST plots. Higher infiltration rates from SS treatment are expected to produce significantly less surface runoff due to a deeper permeable amended soil profile that can retain significantly more soil water. The SS treatment created an enriched landscape that delivered a superior portfolio of environmental services.

5.4 Management Implications

The results strongly suggest that enhanced services from SHA property can be achieved by actively aligning site plans, specifications, grading and landscaping practices, with expected outcomes, to achieve multiple goals – including greatly enhanced hydrologic services with deeper rooted vigorous vegetation, in addition to essential site stabilization goals.

SS plots demonstrated great potential to improve long-term vegetation success while meeting multiple site goals through revised landscaping specifications. Although this study did not field-test additional practices, the Extended Literature Review in Appendix A identifies a range of grading and construction practices, remediation techniques, and management actions that can be integrated into SHA specifications to effectively avoid and mitigate soil compaction. *A priori* identification and definition of desired services across a site allows for improved lifecycle management of soil and landscape services throughout design, construction, remediation and maintenance efforts. The synthesis of practices identified in the Extended Literature Review (Appendix A) led to a recommendation that SHA consider modifying its specifications and standards in order to explicitly prioritize goals for stability, vegetation success and hydrologic function on every SHA project site and landholding. A simple pragmatic approach to this "outcome-based management" is suggested that assigns every distinct sub-area of a site or project footprint to one of three distinct land-use-outcome categories, described in Table 5. These categories are based on the expected goals and services expected from the final project footprint. This "outcome-based" approach to site development provides a life-cycle framework for managing soil compaction on SHA sites. The brief summary in Table 5 aligns the goals, typical land uses, and recommended techniques throughout the development process, complementing standard site plans for grading, temporary erosion control, and final planting plans.

Table 4 - Classification for managing soil compaction based on outcomes.

Class	Prioritization of Outcomes:			Typical Land Use	Management Techniques and Target Density
	Stability	Vegetation	Hydrology		
1	highest priority	n/a	n/a	Roadbeds and Building foundations.	Intentional compaction to achieve contract specified target density (e.g. 95% proctor density)
2	high priority	medium priority	medium priority	Areas that will not bear structures, but should be capable of bearing occasional vehicle traffic (e.g. Shoulders and Medians) Slopes 3:1 or gentler.	Avoiding excessive compaction by matching equipment to soil properties. Organic matter can support vegetation that in turn improves stability. Compact to 80-85% proctor density under dry-side conditions.
3	low priority	high priority	high priority	Areas that must support vegetation and infiltration but are not intended for traffic.	Protect from vehicle traffic, or match equipment to soil. Loose tipping for topsoil placement. Rip or completely cultivate unintended compaction. Compost incorporation. Targeted to “native” density from pedotransfer function

6. Conclusions

The primary objectives of this research were to:

1. Demonstrate and evaluate innovative subsoiling, soil amendment, and vegetation choices to improve vegetation establishment and improve hydrologic function in the disturbed and compacted soils of SHA median and roadside rights-of-way.

2. Evaluate use of SHA compost as a beneficial soil additive for landscaping improvement

3. Evaluate effectiveness of alternative vegetation choices selected for deep rooting characteristics to maintain soil structure and health.

4. Develop and test revised grading and site preparation specifications to avoid and mitigate soil compaction during construction operations.

Initial assessment of the Taneytown project site showed pervasive significant compaction on areas disturbed by SHA activity. The roadbed had significantly higher BD than the staging area, consistent with more methodical compaction to load bearing standards for roadbed construction. Both the roadbed and the staging area were significantly more compacted than the surrounding area on the project site that had not been intensely disturbed during construction.

The project results show that SHA's current specification 705 for turf establishment can eventually produce acceptable cover for vegetative stabilization if it is carefully implemented and monitored, including re-seeding and overseeding in areas realizing less than 95% coverage. Despite the successful turf cover eventually established on both SS and ST plots with standard turf establishment, the environmental services realized from suburban subsoiling were dramatically superior to the ST plots. Data from the first year after treatment showed ST plots remained compacted with cone penetrometer profiles, soil organic matter, bulk density, and infiltration rates that were not significantly improved from the pre-treatment conditions. In contrast, SS plots resulted in long-lasting decompaction that created rooting potential to at least 12 inches, with significantly higher persistent organic matter and infiltration rates that were roughly 100 times greater than pre-treatment or ST conditions. Dramatic reductions in stormwater runoff can be achieved by managing soils to restore infiltration. Although vegetative cover was ultimately acceptable on almost all plots, the results demonstrate the richer portfolio of environmental services that can be obtained by managing the pervious landscape for multiple outcomes.

Objective 1: Demonstrate and evaluate soil remediation for SHA

The project results demonstrated the superior persistent enhancement of soil properties, vegetation success and the dramatic increased in infiltration from suburban subsoiling.

The suburban subsoiling plots clearly demonstrate the efficacy of ripping and compost amendment for mitigating compaction in both the roadbed and staging area soils. The distribution of SS cone index profiles shows dramatic consistent decompaction to depths of 9-12 inches, with significantly greater organic matter content. Mean infiltration rates approximately 2 orders of magnitude greater than standard turf plots underscore the dramatic restoration of hydrologic function to significantly compacted soils using suburban subsoiling. The results of this project demonstrate significant benefits from incorporating suburban subsoiling to mitigate compacted soils on SHA projects. When combined with deep ripping using a Class II parabolic ripping blade on an SHA mowing tractor, the less common use of ***soil spading*** equipment was *extremely* effective in incorporating surface applied compost uniformly throughout the 9-14 inch depth of incorporation that was realized. These results are superior to any use of ripping and rotary tillage the research team previously observed.

Objective 2: Evaluate the use of SHA deer compost

SHA deer compost proved to be an effective source of organic matter as compost amendment.

The very mature compost had lower organic matter content than mature Leafgro compost and a low C:N ratio that should not limit plant available nitrogen. The mature deer compost used in this project provided stable soil carbon with nutrients overwhelmingly delivered in organic forms, minimizing the risk of nutrient losses or leaching when properly applied and soil-incorporated.

Objective 3: Evaluate *Daikon* radish to mitigate compacted soil

The success of radish plantings demonstrated the efficacy and success of seed-drillings as a minimally disruptive method to establish forage radish on SHA property. The significant radish development on plots with successful germination demonstrated the potential for biodrilling as a low-impact multi-year strategy to mitigate compaction on similar SHA properties. Further research is warranted to (a) identify the compaction limits for biodrilling success; (b) improve the germination reliability for seed-drilled radish; and (c) evaluate the cumulative effects of multi-year seed-drilled radish treatments. Useful results from future work can be readily derived from additional site characterization of the Taneytown radish plots after the winter of 2015-2016, and from repeating seed-drilling in 2016 to evaluate multi-year biodrilling.

The radish plots demonstrate that seed drilling can be an efficient effective means to establish forage radish on SHA sites with minimal surface disturbance, and without the need for a separate sediment erosion control plan or permit. The inter-plot variability in vigor among the plots suggests site conditions may be at or near the limits of growth limiting bulk density for the radish. One of the less vigorous plots in the staging area had ~1 square yard of vigorous growth around an animal burrow, suggesting bulk density-limited growth on the remainder of the plot. SA plots with smaller radishes still created macropores and develop a supporting network of finer roots in the soil. The radish growth is expected to have a significant effect on soil porosity after frost-kill. The research team hypothesizes that the lower vigor in first year plantings can be built upon in subsequent years to develop a low-cost multi-year site preparation practice via repeated fall plantings. Results to date give indications of success; variability of these results suggest the need for further work to (a) evaluate bulk density limitations; and (b) confirm cumulative effects from multi-year planting and cultivation. Further work is warranted to evaluate the use of forage radish as part of a low-tech low-cost multiyear site-preparation practice.

Objective 4: Develop and test revised specifications to avoid, limit, and mitigate compaction

The project recommended an "outcome-based" approach to managing grading and compaction on every SHA project by defining distinct zones prioritized by expected outcomes for (a) vegetation success; (b) hydrologic services; and (c) stability. Incorporating outcome-based recommendations from initial site design through construction, inspection, and long-term maintenance, provides a consistent framework to match grading, site preparation, stabilization, maintenance practices, and equipment choices, to site-specific soil and field conditions.

The synthesis of practices identified in the Extended Literature Review led to the simple pragmatic "outcome-based management" approach summarized in Table 5. Designating every distinct sub-area of a site or project footprint to one of three distinct land use-outcome categories based on the expected goals and services expected from the final project footprint, provides a life-cycle framework for managing soil compaction on SHA sites. The extended literature review provides detailed information regarding revised grading and site preparation specifications to avoid and mitigate soil compaction during construction operations including:

- The outcome-based framework for site design and construction operations to prioritize explicitly desired outcomes for soil strength and stability, vegetation success, and hydrologic services, across the site
- Improved practices for topsoil placement
- Identifying vehicle and soil characteristics to avoid undesired compaction during construction, as well as standard landscaping, seeding and mowing operations.
- Identifying vehicle and soil characteristics to maximize the effectiveness of decompaction activities
- Target densities and soil moisture conditions to maximize hydrologic function and vegetative success without compromising soil stability
- Combine decompaction techniques with aggressive compost amendment to achieve a sustainable highly functional soil profile.

Beyond the primary goals for the research, the project undertook an extensive literature review which was provided as an internal reference document for SHA. The extended literature review included a more detailed examination of (a) measures of soil health and their applicability for SHA (b) mechanisms and criteria for soil compaction; (c) more detailed review of the relationship between equipment operating characteristics, soil properties and compaction vulnerability. The larger literature review led to a functional synthesis for SHA purposes (including specific operational guidance for SHA New Holland mowing tractors) to indicate conditions with excessive compaction risks. The literature review also led to a framework for recommended practices in SHA projects, in which the total site footprint is managed for multiple objectives, balancing functional stability, vegetative success and hydrologic services.

Based on the extended review of the literature (provided as an internal reference document for SHA) it can be recommended that SHA modify its procedures to prioritize stability, hydrologic services, and vegetative success for each distinct sub-area of the SHA project footprint, property, and right-of-way in order to implement the findings of this research. The pragmatic priority set among these potentially competing goals provides a consistent framework to align means and methods, equipment specifications and choices, and expected outcomes, to enhance vegetative success and environmental services while delivering sustainable multifunctional landscapes from SHA projects.

These findings are appropriate to apply to SHA projects as a low cost, low risk approach to revitalizing compacted soils. Abandoned roadbeds of sufficient size and scale will benefit from subsoiling and biodrilling techniques to ameliorate soil compaction prior to planting or revegetating the site. Application of forage radishes will be more suitable for existing meadows and other appropriate roadside landscape management areas.

Cultivating deep permeable organic soil profiles by adapting these land development practices will result in reduced life-cycle costs for green asset maintenance. SHA can include these techniques in the designer's toolbox for consideration on a site by site basis to promote long term landscape sustainability.

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Appendix A – Informed Field Operations for SHA: An Example Using the Taneytown Project Site

Appendix A: Informing Field Operations

Here we present a pathway for informing field operations like mowing, aerating, tilling, seed drilling, planting, ripping, etc.

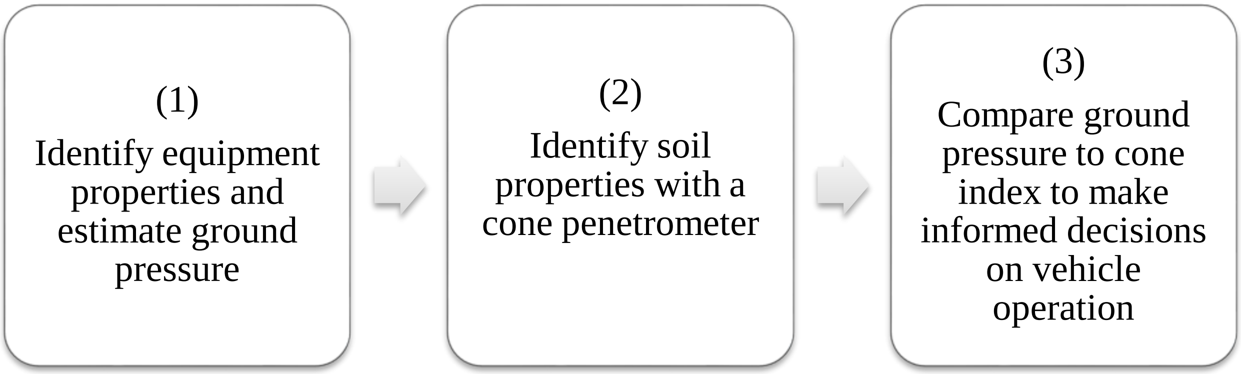

Figure A16 - basic framework for informing field operations

Step One: Determine Ground Pressure

Ground pressure can be estimated from tire dimensions and vehicle load. However, under an ideal set of conditions, ground pressure is comparable to tire pressure. Hakansson et al. (1988) describe this relationship:

> *”A relatively flexible pneumatic tire with a moderate inflation pressure, running on moderately-firm soil, exerts a ground pressure of the same magnitude as the tire pressure… Carcass stiffness may cause a higher average ground pressure than the inflation pressure… A tire with a stiff carcass acts as a rigid wheel* [invalidating the relationship between inflation and ground pressure]*… on a soil with very low bearing capacity, even a relatively flexible tire with moderate inflation may act similarly to a rigid wheel”*

This suggests that when using radial tires (which are more flexible than bias ply tires) that are properly inflated (based on manufacturer recommended minimum inflation pressure for a given load) on a moderately firm soil (soil which has not been recently tilled), the inflation pressure can be used as a surrogate for ground pressure.

If these assumptions are not met, we can also estimate ground pressure using simple contact area models. O’Sullivan et al. (1999) show contact area in m^2 (A) can be calculated as:

$$A = s_1 bd + s_2 L + \frac{s_1 L}{p_i} \tag{1}$$

Where L is tire load (kN), b is tire width (m), d is tire diameter (m), and p_i is inflation pressure in kPa. The parameters s_1, s_2, and s_3 and are taken from table 1 below. O’Sullivan et al. (1999) only reported values for Rigid and Soft soil; the Moderate values are simple linear interpolations.

Table A5 - Parameters for estimating contact area

Constant	Rigid Soil (BD > 1.8 g/cc)	Moderate Soil	Soft Soil (BD < 1.0 g/cc)
s_1	0.041	0.1755	0.310
s_2	0	0.0013	0.00263
s_3	0.613	0.426	0.239

O’Sullivan et al (1999) suggest that radial tires (as opposed to bias ply tires) be represented by a 20% increase the contact area estimate. Ground pressure is calculated as the load for a single tire divided by the contact area. The simplest derivation of single tire load is simply 25% of the total tractor weight, which assumes even weight distribution between front and rear axles. Using data presented by Stokes and Claar (2004) for equipment comparable to MD SHA New Holland tractors, we assume a 60/40 split between the rear and front axles. The standard MD SHA New Holland Tractors (TS 90 and TS 100) weigh approximately 8664 pounds. Table 2 describes tire properties for SHA New Holland tractors.

Table A6 - Tire Properties

Axle	Model	Width (inches)	Diameter (inches)	Load per tire (pounds)	Recommended Inflation Pressure (PSI)
Front	7.50-16	7.5	31.5	1732	30
Rear	16.9-30	16.9	58.5	2599	12

Recommended inflation pressures come from Titan Tires[9] recommendations based on load for a 7.50-16 bias ply tire, shown in table 3. For a 16.9-30 bias ply tire, the minimum inflation of 12 PSI can support 3000 pounds.

Table A7 - Inflation Pressures

Inflation (PSI)	24	28	32	36	40	44	48	52
Load (lbs)	1480	1650	1820	1930	2090	2200	2340	2470

Using knowledge of the tractor load and tire dimensions, we can use equation 1 to estimate ground pressure across a range of tire inflation pressures, shown in table 4.

Table A8 - Ground Pressure Estimates for New Holland Tractors

Tire	Tire Inflation Pressure (PSI)	Ground Pressure Estimate (PSI) for Bias Ply Tires on:		
		Soft Soil	Moderate Soil	Hard Soil
Rear Tire (16.9-30)	10	6.3	10.2	13.0
	12	6.4	11.2	15.0
	18	6.7	13.4	20.1
	20	6.8	14.0	21.6
Front Tire (7.50-16)	24	14.2	19.7	32.2
	30	14.6	21.2	38.5
	36	14.9	22.3	44.3
	42	15.1	23.2	49.6

On a moderately firm soil with recommended inflation pressures of 12 PSI for the rear tire and 30 PSI for the front tire, we estimate a ground pressure of 11 PSI for the rear tire and 21 PSI for the front tire.

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[9] http://www.titanstore.com/pdf/LoadandInflation.pdf

Step Two: Cone Index Survey

Using a simple cone penetrometer, take cone index profiles across the site. Make note of the average cone index in PSI in the top 8 inches of the soil profile. This survey does not need to be precise, just enough to capture the overall properties of the soil. Is the cone index in the range of 200-300 PSI? 400-500 PSI? Greater than 600 PSI?

Step Three: Inform Field Operations

The estimated ground pressure, multiplied by a factor of 20, will determine the minimum acceptable cone index of a soil that can support that load without compacting. For example, if the maximum estimated ground pressure from a vehicle is ~20 PSI, then the characteristic cone index of the soil profile should not be significantly below 400 PSI in order to avoid compaction.

Conversely, a cone index survey can help identify the maximum allowable ground pressure or tire pressure for the vehicles. Multiply the cone index by 0.05 to determine the max ground pressure. If the soil profile shows cone index of ~400 PSI, but the maximum ground pressure from the equipment is 25 PSI, the vehicle should not be operated. However, if this vehicle were equipped with radial tires, the contact area would increase, in turn decreasing the ground pressure to the point that the vehicle should no longer result in compaction.

Fritton (2008) acknowledges that this 20:1 ratio of cone index to ground pressure is highly conservative, and that additional research is necessary to determine if a ratio of 15:1 or even 10:1 would be appropriate. If managers notice that there is not any visibly apparent rutting, compaction or other soil damage, they may consider relaxing these constraints slightly.

The characteristic cone index of the soil profile should be above 400 PSI in order to minimize the risk of compaction from SHA New Holland Tractors.

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