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Urban Soil Compaction Remediation by Shallow Tillage and Compost in Hydroseeded Lawn

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Abstract

Construction activities often involve removal of topsoil and compaction of the exposed soil by heavy equipments. Such compacted soils with low organic matter can lead to low infiltration and poor vegetation establishment. The objective of this study was to investigate the efficacy of tillage (shallow till) and compost on soil physical and biological properties in a hydroseeded lawn as a post-construction best management practice for soil compaction remediation. The experimental site received a total of four land treatments in five replicated trials and it was hydroseeded with common Bermuda grass: 1) No Tillage + Compost (NT-C), 2) No Tillage + No Compost (NT-NC; control), 3) Tillage + Compost (T-C), and 4) Tillage + No Compost (T-NC). Bulk density (BD), infiltration rate (IR), and wet aggregate stability (WAS) in each plot were measured to assess soil physical properties while soil organic matter (SOM) and enzyme activity (β-glucosidase, acid-phosphatase, and alkaline-phosphatase) were measured for soil biological properties. Over a 15-months of monitoring period, the shallow tillage loosened the soil initially, but its effect on BD without compost was diminished to control plot level (NT-NC) within 4 months after hydroseeding. Both tillage and compost led to an increase in IR, and it remained higher than control by 2 - 3 times throughout the observation period. The WAS and β-glucosidase activity decreased in tilled plot unless there was compost application. Turfgrass showed greener leaves and aggregated roots in the compost-amended plots (NT-C and T-C). Our results suggest that compost application plays a key role in improving soil physical and biological properties in hydroseeded lawns from construction sites.

Keywords

Compaction, Compost, Infiltration, Soil Organic Matter, Soil Enzyme, Tillage,

Wet Aggregate Stability

1. Introduction

Texas is one of the fastest growing US states with a 6% population growth rate since 2020 and the rapid urbanization accompanied this population growth [1]. Urban development and the associated construction activities often cause unintentional soil compaction by removal of topsoil, excavation, and heavy equipment traffic. Threshold bulk density (BD) that can restrict root growth is >1.8 $g \cdot cm^{-3}$ for sandy soils, >1.65 $g \cdot cm^{-3}$ for silty soils, and >1.47 $g \cdot cm^{-3}$ for clayey soils, and clayey soils under wet conditions are more susceptible to compaction [2]. Previous studies have demonstrated soil BD exceeding these levels by construction activities [3] [4]. Severe soil compaction can limit vegetation establishment, reduce infiltration rate (IR), and result in increased runoff and sediment loss from the site [5] [6]. Consequently, the site can become more prone to surface sealing, water ponding, and local flooding [7].

Improving infiltration in compacted urban soils is an important hydromodification approach that enables rainwater to soak into the ground to reduce runoff and peak flow [8]. Tillage and compost are potential options to remediate compacted urban soils [5] [6] [8] [9]. Haynes *et al.* (2013) found that deep tillage in compacted soils in North Carolina Piedmont region, USA (sandy clay loam) increased average IR up to 15 $cm \cdot h^{-1}$ compared to control (0.16 $cm \cdot h^{-1}$) [5]. Mohammadshirazi *et al.* (2017) compared tillage with and without compost application in compacted soils in North Carolina, USA [6]. The IR in tilled plots was about 3 - 5 times greater than control plots, while compost alone without tillage did not increase IR significantly over 2-years of monitoring period. In Florida urban soils, Olson *et al.* (2013) found that deep tillage alone did not increase IR consistently over time unless compost was also incorporated, indicating contrasting effects of compost on IR between studies [8].

Soil health is a growing concept defined by "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" [10]. Soils in construction sites can be characterized by lack of soil organic matter (SOM) and stable aggregates as topsoil is removed at the site and grading operation exposes subsoil [6]. Tillage can have both positive and negative effects on the soil health. While tillage helps break up compacted soil and control weeds in the short term, frequent tillage can lead to accelerated soil erosion, loss of organic matter, and disruption of soil structure over time [11] [12]. Adding compost is an established practice for urban landscaper and it has been recognized as a reliable amendment that can improve soil health, particularly in soils with poor structure and low organic matter [13] [14].

The goal of this study was to investigate the effects of shallow tillage with and without compost amendment on selected soil physical and biological properties after hydroseeding (hydraulic mulch seeding) in a post-construction site in South Texas, USA. Hydroseeding is a common grass planting technique in USA by spraying grass seed, mulch, and fertilizer together over large areas or slopes after construction. Shallow tillage was chosen in this study due to the potential infeasibility of deep tillage in certain urban settings (e.g., tree interference, utility line, and small remediation areas) [8]. The specific study objectives were 1) to evaluate the effects of shallow tillage and/or compost on BD and IR over time (15 months), 2) to evaluate the effects of shallow tillage and/or compost on wet aggregate stability (WAS), SOM, and enzyme activity in the tested plots, and 3) to examine turfgrass characteristics influenced by tillage and/or compost treatments.

2. Materials and Methods

2.1. Site and Land Treatment Description

This study was conducted at the University of Texas Rio Grande Valley (UTRGV) Edinburg campus located in Hidalgo County, Texas, USA (Latitude of 26˚18’16.84", and longitude of 98˚10’21.63"). Hidalgo County has a subtropical, semi-arid climate with an average annual precipitation ranging from 50 to 60 cm [15]. The precipitation is primarily concentrated during May to July and Sept to October. The experiment site covering approximately 0.5 ha was classified as the Hidalgo-Urban complex with slopes ranging from 0 to 1%. The soil is listed as fine-loamy, mixed, active, hyperthermic Typic Calciustolls according to the USDA Soil Classification [16]. The site had been previously leveled and graded for UTRGV Science building construction.

The site preparation began as bare soil in May 2018 (**Figure 1**). Particle size analysis was conducted on the initial surface soil (0 - 15 cm) using the hydrometer method [17]. The soil contained 71% sand, 3% silt, and 26% clay (sandy clay loam), the soil pH was 8.5 (1:1 deionized water to soil ratio), and initial BD ranged from 1.3 to 1.5 g·cm^{-3}. The site received a total of four different land treatments in five replicated trials on a randomized complete block design: 1) No tillage + Compost (NT-C), 2) No Tillage + No Compost (NT-NC; control), 3) Tillage + Compost (T-C), and 4) Tillage + No Compost (T-NC). A landscape weed barrier (30-cm in width) was installed in the perimeter of each plot to separate experimental treatments. Compost was obtained from the City of McAllen Composting Facility (Texas, USA) and it was applied in 5-cm thickness (approximately 300 Mg·ha^{-1}). The compost material had a carbon-to-nitrogen ratio (C:N) of 30:1 with pH 7.92 and its feedstock was a mixture of ground brush and green waste.

Tillage was done by a rear-tine tiller up to 15 cm in depth (**Figure 1**). For the T-C treatment, compost was incorporated into the soil during the tillage. After the land treatments, a total of 20 plots (each plot sized 3.5-m wide and 4-m long) were hydroseeded with Bermuda grass (mixed variety, Ewing Irrigation Products, Katy, Texas, USA), hydromulch (Oasis fiber mulch brand, Houston, Texas, USA), and fertilizer (NPK of 16-8-8, American Plant Food Corporation, Galena

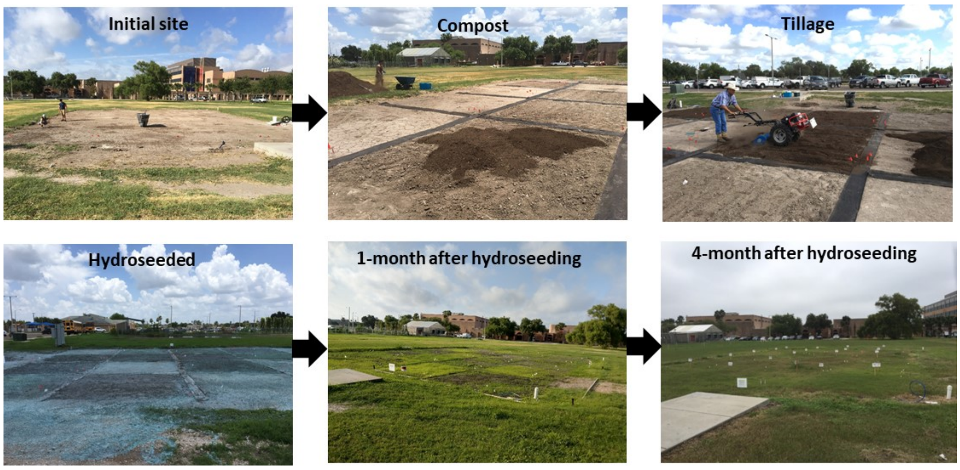

Figure 1. Site establishment, hydroseeding, and vegetation growth.

Park, Texas, USA) by a truck-mounted hydroseeder (T90 hydroseeder, FINN Corporation, Fairfield, Ohio, USA) in July 2018. In-ground irrigation system was operated for the initial two months by a landscaping company, watering twice a day to establish the grass. Following this period, the site relied on natural rainfall without additional water irrigation. After the initial 3 months, lawn mowing was performed every month using a hand-held lawn mower without leaf collection.

2.2. Penetration Resistance and Bulk Density

Penetration resistance (PR) was measured immediately after the site received the land treatments (compost and/or tillage) but prior to hydroseeding, using a cone penetrometer (SC900 Soil Compaction Meter, FieldScout, Aurora, IL, USA). The penetrometer measured soil compaction in psi (pound per square inch) by 1-inch (2.54 cm) interval, and the data were converted to Megapascal (MPa) up to a depth of 25 cm. We observed that the PR meter encountered frequent error messages when it reached the compacted layer in the subsoils. Considering the error messages and subsequent missing PR values, the PR data collection was not performed further after the hydroseeding and only the PR data before hydroseeding is presented to describe initial soil compaction status right after compost and tillage treatments.

Soil BD was measured by an intact soil core sampler (AMS Soil Sampler 404.02, AMS Inc., American Falls, ID, USA) at three different depths (0 - 5 cm, 5 - 10 cm, and 10 - 15 cm). Soil core samples were obtained from individual plots using a 5 cm by 5 cm metal cylinder and they were oven-dried at 105˚C for 24 h (Figure 2(a)). The BD was calculated by a ratio of dry weight of the soil sample to the volume of the soil core. The measurements were repeated at three different time points after hydroseeding (4 months, 9 months and 15 months; October 2018, March 2019, and October 2019).

2.3. Infiltration Rate

The IR measurements in this study were conducted using a Cornell Sprinkle Infiltrometer (CSI; Cornell University, Ithaca, NY, USA) at 4 months, 9 months, and 15 months after hydroseeding (**Figure 2(b)**). The Cornell infiltrometer kit was purchased from the Cornell Soil Health Laboratory (Ithaca, NY, USA) and detailed methodology is available in its manual [18]. Briefly, the infiltrometer had a single metal ring (24.1 cm in diameter) and it was inserted to a depth of 7.5 cm into the soil. In the adjacent of the ring, soil was dug to place a 1-L beaker connected to the ring via a runoff collection tube. The infiltrometer unit was equipped with a portable rainfall simulator with a Marriott siphon tube to achieve a constant head, and small tubes for water irrigation at the bottom. The chamber was filled with tap water and was placed on top of the ring to simulate rainfall. The measurement was initiated with wetting of the soil. As soon as the first runoff was observed, both the runoff volume and dripper water height in the chamber were recorded every 3 minutes until the runoff volume reached a steady state. The infiltration rate was calculated as the difference between dripping (simulated rainfall) rate and runoff rate at the steady state. The average dripping rate was 24 cm·h^{-1} across the measurements and IR values were corrected using a texture-based conversion factor (0.8 for loams) to account for three-dimensional flow at the bottom of the ring according to the manual [18].

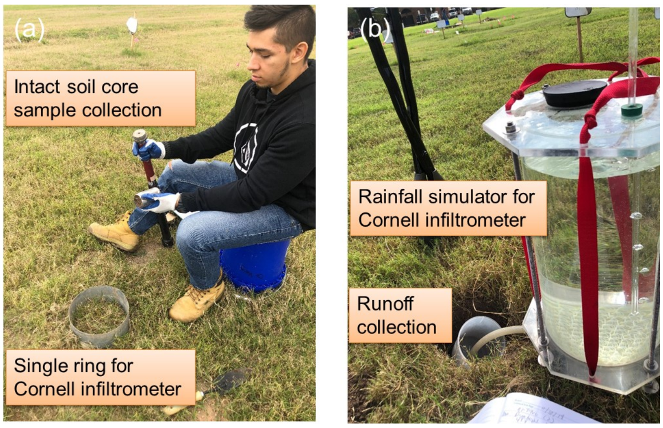

Figure 2. Soil physical property measurement: (a) soil core sampling for bulk density and (b) the Cornell Sprinkler infiltrometer.

2.4. Soil Organic Matter and Wet Aggregate Stability

Composite soil samples from individual (0 - 15 cm) were collected 9 months after hydroseeding (March 2019), air-dried, and screened through a 2-mm sieve. The SOM was measured via loss-on ignition [19]. The WAS was measured using the Cornell wet aggregate stability kit using the Cornell rainfall simulator. This method is based on the force of water droplets on air-dried aggregates and van Es *et al.* (2017) present the detailed procedures [20] [21]. Briefly, a composite soil sample from each plot (0 - 15 cm) was collected, air-dried, and screened through a stacked sieve of 2.0 mm, 0.25 mm, and a catch pan. The soil sample retained in the 0.25-mm sieve (sieve + approximately 100 g of soil sample) was placed in a stand that holds a funnel lined with a filter paper (Qualitive Crepe filter paper with Grade 415 and 38.5 cm in diameter, VWR, Radnor, PA, USA). For the rainfall simulation, the Cornell infiltrometer was raised and hung in a tripod. The height of water dripping tube was 50 cm above the soil sample and water was irrigated for 5-min at a rate of 0.5 cm·min^{-1}. Soil material that passed through the 0.25-mm sieve during the simulated rainfall (slaked soil material; unstable) was collected on the filter paper and weighed after oven-drying the sample overnight at 105˚C. The fraction of stable soil aggregates (in %) representing WAS was calculated using the following equations [21]:

$$\text{WAS}\ (\%) = W_{\text{stable}}/W_{\text{total}} \times 100 \tag{1}$$

where W_{stable} = weight (g) of stable soil aggregates, W_{total} = total weight (g) of aggregates tested. The W_{stable} was determined by:

$$W_{\text{stable}} = W_{\text{total}} - W_{\text{slaked}} \tag{2}$$

where W_{slaked} = weight of slaked soil aggregates (soil retained in the filter paper). In equation (2), the slaked soil aggregates (W_{slaked}) represent unstable aggregate portion of a soil sample that breaks under the simulated rainfall. Note that the percentage of WAS of a soil sample in Equation (1) depends on the dripper height, which determines the total kinetic energy delivered by the simulated rainfall [21].

2.5. Soil Enzyme Activity

The soil samples (0 - 15 cm) collected 9 months after hydroseeding (March 2019) were analyzed for β-glucosidase (BG), acid-phosphatase (AcdP), and alkaline-phosphatase (AlkP) activities. The BG enzyme is involved in the degradation of cellulose in soils and has the potential to predict organic matter decomposition [22]. The BG assay was conducted according to a method by Marx *et al.* (2001) [23]. Initially, 1 g of soil was weighed and placed in an autoclaved jar. Subsequently, 100 ml of sterile water was added to the soil, and the jar was subjected to an ultrasound bath (Branson 3800 Ultrasonic Cleaner, Branson, Germany) for 4 minutes. After the homogenization process, a 25 μL aliquot of the prepared soil suspension was transferred into a microplate (Greiner Bio-One GmbH, Frickenhausen, Germany). The samples received 25 μL of buffer, 50 μL of substrate, and varying volumes of the standards (0, 10, 20, 40, and 60 μL) to create a dilution series of the standard. The buffer used in the assay was a 0.1 M 2-(N-morpholino)ethanesulfonic acid (MES) buffer solution at pH 6.1. The substrate was prepared by dissolving 0.034 grams of 4-methylumbelliferyl b-D-glucopyranoside in 300 μL of dimethyl sulfoxide. To this solution, 10 ml of sterile water was added, and then 5 ml from this mixture was combined with 45 ml of MES buffer to obtain the final substrate solution for the assay. Fluorescence measurements were taken at 30, 60, 120, and 180 minutes using a BioTek Instruments Synergy™ HTX multi-mode microplate reader (Winooski, VT, USA) at 360/460 nm. The fluorescence values were then converted into nmol substrate·g^{-1} soil·h^{-1} using a standard curve with 4-methylumbelliferone added to the soil suspension of each sample. The standard curve was prepared using a 10 μM 4-methylumbelliferon (MUF) solution, which was obtained by diluting a stock solution (10 mM) prepared by dissolving

0.1762 g of MUF in a 100 ml volumetric flask containing 50 ml of methanol and then completing the volume with sterile water.

AcdP and AlkP activities were measured to determine the enzymes' ability to hydrolyze organic P into inorganic orthophosphate, the bioavailable P form in soil. The method of Marx *et al.* (2001), as modified by Poll *et al.* (2006), was employed and detailed protocol is described in Navarro *et al.* (2020) [22]-[24]. Briefly, 1 g of soil was dispersed with 100 ml of sterile water in a jar and the jar was subjected to an ultrasound bath for 5 minutes. The assay was conducted using 25 μl aliquots of the soil suspension on a microplate. The substrate used was 4-methylumbelliferylphosphate. For AcdP and AlkP, 0.1 M 4-morpholineethanesulfonic acid buffer (pH 6.1) and modified universal buffer (pH 11) were used respectively. Fluorescence was measured after 30, 60, 120, and 180 minutes using the same microplate reader at 360/460 nm and converted into nmol substrate·g^{-1} soil·h^{-1} using a standard curve with 4-methylumbelliferone added to the soil suspension of each sample. Enzyme activity was calculated according to the standard curve, as it was found to be linearly related to the intensity of fluorescence.

2.6. Turfgrass Characteristics

Turfgrass characteristics were examined by grass leaf chlorophyll concentration by SPAD (Soil Plant Analysis Development) value, dry root mass, and carbon (C) and nitrogen (N) of the aboveground biomass (grass samples). About 9 months after hydroseeding (March 2019), the greenness of the turfgrass was measured by a chlorophyll meter (SPAD-502 Plus, Konica Minolta Inc., Remsey, NJ, USA). The grass and root samples were collected by inserting a 7.5-cm by 7.5-cm metal cylinder to the soil surface in each plot. The grass part was clipped, oven-dried, and measured for C and N using an elemental analyzer (ECS 4010 Nitrogen/Protein Analyzer, Costech Analytical Technologies, Inc., Valencia, CA, USA). The root portion was carefully separated and rinsed with tap water to remove soil particles. The root samples were oven-dried at 105˚C and weighed to calculate the dry root mass in unit area (mg·cm^{-2}).

2.7. Statistical Analyses

Analysis of variance (ANOVA) using the PROC GLM procedure was performed with two independent variables (tillage and compost) and their interactions on dependent variables (BD, IR, WAS, SOM, C and N contents of grass, and dry root mass) using SPSS version 28 (IBM Corporation, 2021). The multiple-time measurements for BD and IR data were treated with repeated measures for ANOVA analysis. Primary treatment effects were evaluated using Tukey's multiple comparison test.

3. Results and Discussion

3.1. Soil Penetration Resistance and Bulk Density

The PR data (measured after the land treatment but prior to hydroseeding; June

2018) showed that soil compaction increased with increasing depth in the experimental plots (**Figure 3**). For the surface soil (0 - 15 cm), a PR value > 1.38 MPa (200 psi) is considered a compaction level that can limit root growth [25]. The control plot (NT-NC) exceeded this threshold at most depths except for the very topsoil (2.5 cm). Tillage ameliorated soil compaction up to 10 cm but the PR values below 12.5 cm were not significantly different between treatments, reflecting the depth of shallow tillage (up to 15 cm). The effect of the compost was significant only up to 5 cm deep, and all plots showed > 1.38 MPa below 15 cm deep.

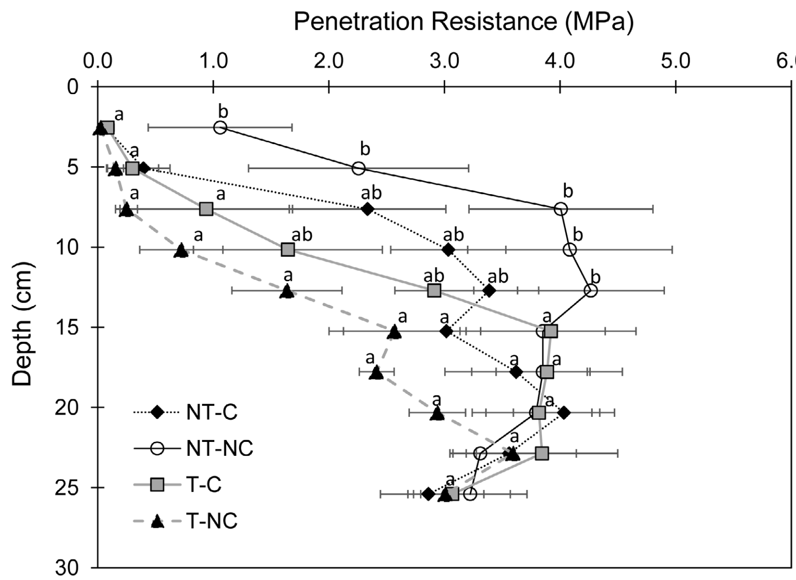

Figure 3. Soil penetration resistance by depth. Error bars represent a standard deviation from 5 replicated plots and same letters within each depth are not statistically different (p = 0.05).

The BD ranged from 0.67 to 1.78 g·cm^{-3} depending on the land treatment and sampling depths (**Figure 4**). The control plot (NT-NC) had BD > 1.28 g·cm^{-3} at 0 - 5 cm, >1.40 g·cm^{-3} at 5 - 10 cm, and >1.41 g·cm^{-3} at 10 - 15 cm. The BD values in our control plot (0 - 15 cm) were lower than those with compacted soils having similar texture (BD range of 1.5 - 1.6 g·cm^{-3} in sandy clay loam/sandy clay texture reported in other studies [5] [6] [9]. Our data indicates that the 5 - 15 cm depth of soils were not loosen as much as the top 5 cm by shallow tillage. For 0 - 5 cm BD, compost had a significant effect on BD and its effect stayed significant over time ($p < 0.001$). For example, the 0 - 5 cm BD values in NT-C and T-C (0.75 - 1.08 g·cm^{-3}) were significantly lower than those in NT-NC and T-NC (1.19 - 1.45 g·cm^{-3}) (**Figure 4(a)**). This result can be explained by the 5-cm compost application, which lowered the BD. For 5 - 10 cm depth (**Figure 4(b)**), the tilled plot with compost (T-C) showed slightly lower BD, but the difference was not significant compared to other treatments. There was no significant difference in 10 - 15 cm BD between treatments (**Figure 4(c)**).

Overall, tillage had no significant effect on BD at any depths when averaged

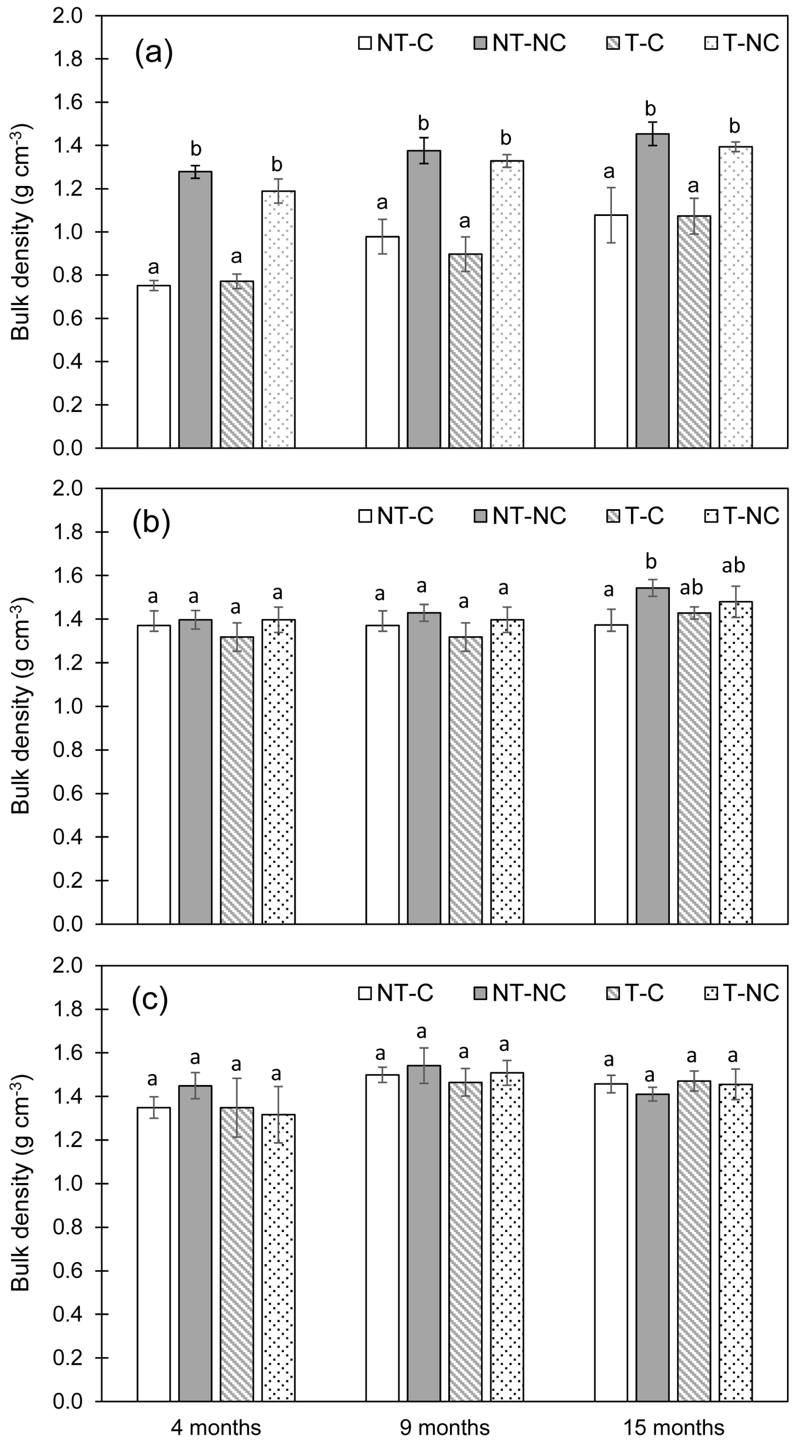

Figure 4. Soil bulk density by the number of months after hydroseeding and depths: (a) 0 - 5 cm, (b) 5 - 10 cm, and (c) 10 - 15 cm. Error bars represent a standard deviation of the means from 5 replicated plots and same letters within each depth are not statistically different ($p = 0.05$).

over time periods (**Table 1**). Note that current study used a shallow till (up to 15 cm), and the effectiveness of tillage in reducing BD diminished within 4 months, and BD increased over time, particularly in the top 5 cm of the soil (**Figure**

4(a)). Soil reconsolidation (settling) is a common process of restoring tilled soil to its pre-tillage condition and it is often induced by wetting-drying cycle [26]. Our study site was watered by in-ground irrigation system for the first two months after hydroseeding, which could have facilitated the soil reconsolidation. Cassel (1983) found that tilled agricultural soils under natural rainfall showed an increase in BD due to the soil reconsolidation (settling) from the first two rainfall events [27]. Soil can be reconsolidated by raindrop impact and the soil matrix can collapse under its own weight, thus reducing the size and number of macropores [28] [29]. Tilled soil might also experience slaking and dispersion of soil aggregates by raindrop impact on the surface, causing the formation of surface crust [30].

3.2. Infiltration Rate

Both tillage and compost improved the IR and remained significantly higher than the control (NT-NC) by 2 - 3 times over time (**Figure 5**). The compost-amended plots without tillage (NT-C) showed the highest IR (11.1 ± 4.5 cm·h^{-1}),

Table 1. Summary of ANOVA table p-values.

Land treatment	Bulk density (0 - 5 cm)	Bulk density (5 - 10 cm)	Bulk density (10 - 15 cm)	Infiltration rate	Wet aggregate stability	Soil organic matter
Tillage	0.304	0.425	0.549	0.037	<0.001	0.013
Compost	<0.001	0.013	0.699	0.001	<0.001	<0.001
Tillage * Compost	0.602	0.810	0.674	0.005	<0.001	0.057
	β-glucosidase	acid-phosphatase	alkaline-phosphatase	Turfgrass C	Turfgrass N	Root mass
Tillage	0.651	0.381	0.065	0.100	0.546	0.550
Compost	0.018	0.244	0.453	0.055	0.429	0.245
Tillage * Compost	0.737	0.818	0.537	0.096	0.051	0.308

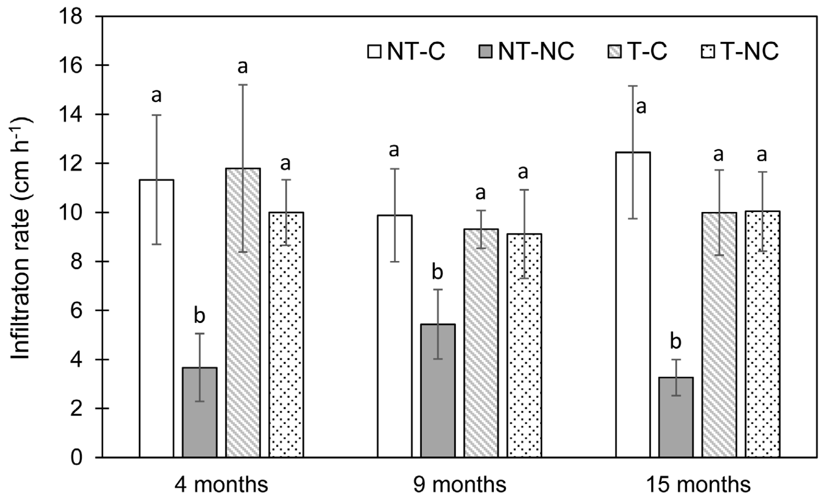

Figure 5. Infiltration rate by the number of months after hydroseeding. Error bars represent a standard deviation of the means from 5 replicated plots and same letters are not statistically different ($p = 0.05$).

followed by T-C (10.3 ± 4.1 cm·h^{-1}), T-NC (9.7 ± 3.0 cm·h^{-1}), and NT-NC (4.1 ± 2.6 cm·h^{-1}) when averaged across time periods. The IR values in current study fell within the IR range (0.5 - 39.5 cm·h^{-1}) by the Cornell infiltrometer measured for similarly textured soils in other studies [5] [6] [9]. It is important to note that the Cornell infiltrometer uses a single ring, which could potentially allow lateral flow of infiltrating water below the ring [6]. Thus, the consistently higher IR values in NT-C may be due to the lateral flow enhancement by compost amendment on the topsoil while the tillage effect on IR was diminished over time.

3.3. Wet Aggregate Stability and Soil Organic Matter

The WAS (% stable aggregate) ranged from 14% to 33% on average across the land treatments (**Table 2**). Both tillage and compost and their interaction had a significant effect on WAS (**Table 1**). No tillage with and without compost (NT-C and NT-NC) had the top two WAS values (29% - 33%) while tillage with no compost (T-NC) had the lowest WAS (14%). This result indicated that tillage reduced WAS in the tested plots. The tilled plot with compost (T-C), however, showed comparable WAS (28%), suggesting that compost amendment contributed to soil aggregation in the tilled plot.

Table 2. Wet aggregate stability (WAS), soil organic matter (SOM), soil enzyme activity at 9 months after hydroseeding.

Land treatment	WAS (%)	SOM (%)	Soil enzyme activity (nM MUF·g^{-1}·h^{-1})		
			β-glucosidase	acid-phosphatase	alkaline-phosphatase
No Tillage + Compost	32.8 ± 4.5^{a}	13.4 ± 1.5^{a}	101.9 ± 57.6^{a}	198.4 ± 74.4^{a}	47.0 ± 28.2^{a}
No Tillage + No Compost	29.0 ± 4.8^{a}	1.3 ± 0.8^{c}	38.3 ± 14.9^{ab}	150.3 ± 74.1^{a}	44.8 ± 35.9^{a}
Tillage + Compost	27.6 ± 1.1^{a}	9.8 ± 2.6^{b}	76.8 ± 68.5^{ab}	160.6 ± 76.3^{a}	88.9 ± 49.0^{a}
Tillage + No Compost	14.4 ± 2.5^{b}	0.7 ± 0.7^{c}	28.6 ± 23.0^{b}	128.1 ± 73.1^{a}	66.5 ± 25.1^{a}

[a]In each column, means followed by the same letters are not significantly different ($p = 0.05$). Error bars represent a standard deviation of the means from 5 replicated plots.

The SOM values ranged from 0.7 to 13.4 g·kg^{-1} in the tested plots and adding compost increased SOM level significantly (**Table 1** and **Table 2**). Compost-amended plot with no tillage (NT-C) had the highest SOM (13.4 g·kg^{-1}) followed by T-C (9.8 g·kg^{-1}), NT-NC (1.3 g·kg^{-1}) and T-NC (0.7 g·kg^{-1}). The linear regression between SOM and WAS yielded the coefficient of determination of 0.36 ($R^2 = 0.36$), indicating 36% of variability of WAS was explained by SOM in a linear regression model (**Figure 6**). Further examination of data points by the land treatments implied followings: 1) Control plot (NT-NC) yielded relatively higher WAS although it had lower SOM; 2) Tilled plot with no compost (T-NC) yielded the lowest SOM and WAS; 3) Compost-amended plot with no tillage (NT-C) showed the highest SOM and WAS overall. These indicated that no tillage was favorable for stable aggregation while compost amendment promoted the soil aggregation. Note that the WAS in current study represents how well a soil can resist raindrop impact and water erosion [20]. Lower SOM in T-C compared to

NT-C may be attributed to the tillage effect that promoted greater SOM decomposition in the compost-amended plots. Our results also suggest that compost amendment improved WAS by increasing SOM level in the tilled plots as SOM is mainly responsible for the stabilization of soil aggregates [31].

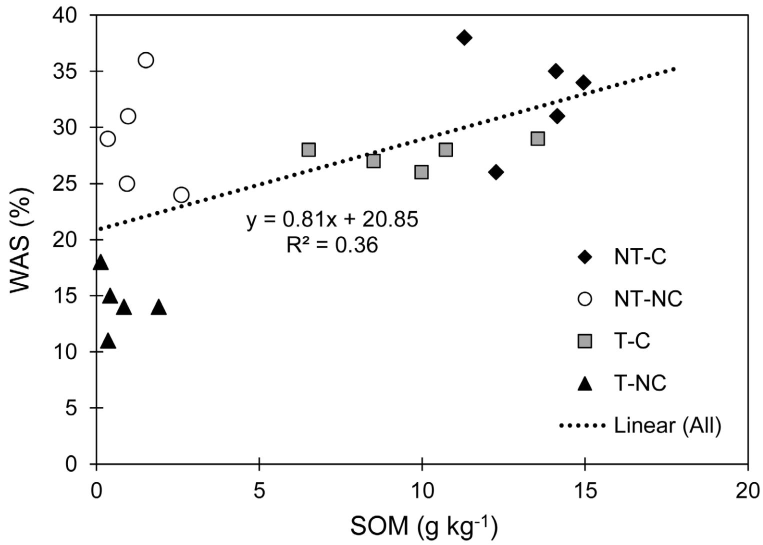

Figure 6. The correlation between soil organic matter (SOM) and wet aggregate stability (WAS).

3.4. Soil Enzyme Activity Analysis

This study measured the activity of the BG, which completes the final step of cellulose hydrolysis by converting cellobiose to glucose [32]. A high BG activity not only indicates a healthy soil condition through enhanced microbial activity but also suggests the provision of essential ecosystem services, including the degradation of soil organic matter and plant residues [33]. Overall, compost application boosted BG activities in current study (**Table 2**). With the given large variability of the data, only compost-amended plot with no tillage (NT-C) showed significantly higher BG activity than tilled plot with no compost (T-NC) by 3.5 times. Higher BG activity by compost-amended plots was likely a response to the higher level of SOM derived from compost material. Previous studies found that compost-amended soils have higher BG activities compared to soils with no compost (non-compost treatment). For example, Pascual *et al.* (1998) found that after 1 year of compost application, BG activities were 1.7 times higher with compost amendment than those with non-compost treatment in a clay-loam soil [34]. Garcia-Gil *et al.* (2000) applied compost produced from municipal solid waste, and after 3 years, BG activities were 1.8 times higher in compost-amended plots than those without compost in sandy soil [35]. Hernandez *et al.* (2015) applied domestic household-based compost in a calcic soil in Spain and found that the BG activities were 3.1-times higher in composted plots than those without compost after 1 year and maintained higher even after 5 years [36]. Assuming a decrease in compost's effect on BG activities over time and its potential to release nutrients to plants, an optimum frequency of compost reapplication is worth being investigated in future studies.

In the current study, tillage nor compost did not show a statistically significant effect on the activities of AcdP and AlkP with the given large variability (Table 1 and Table 2). However, the activities of AcdP were slightly higher with compost-amended plots (NT-C and T-C) than those without compost (NT-NC and T-NC). The activities of AlkP were opposite where tilled plots (T-C and T-NC) were higher compared to no-tilled plots (NT-C and NT-NC).

3.5. Turfgrass Characteristics

Compost-amended plots exhibited greener grass color supported by SPAD value (Figure 7). The relative greenness of grass measured by chlorophyll concentration (SPAD value) was >40 in compost-amended plots with and without tillage (NT-C and T-C), while the SPAD values without compost amendment (T-NC and NT-NC) were below 23. The N content in turfgrass was slightly higher in T-C followed by NT-NC, but the difference lacked statistical significance (Table 3). No significant difference was found in the C content of the turfgrass across the land

Figure 7. Turfgrass appearance in tilled and compost-amended plots (9 months after hydroseeding).

Table 3. Carbon (C) and nitrogen (N) content of turfgrass and root biomass at 9 months after hydroseeding.

Land treatment	C (%)	N (%)	Root biomass (mg·cm^{-2})
No Tillage + Compost	41.92 ± 0.03[a]	1.32 ± 0.05[a]	25.71 ± 3.00[a]
No Tillage + No Compost	41.85 ± 0.14[a]	1.51 ± 0.06[a]	27.34 ± 3.34[a]
Tillage + Compost	41.93 ± 0.10[a]	1.71 ± 0.09[a]	24.56 ± 2.09[a]
Tillage + No Compost	40.92 ± 0.15[a]	1.29 ± 0.05[a]	6.04[a]

[a]In each column, means followed by the same letters are not significantly different (p = 0.05). Error bars represent a standard deviation of the means from 5 replicated plots.

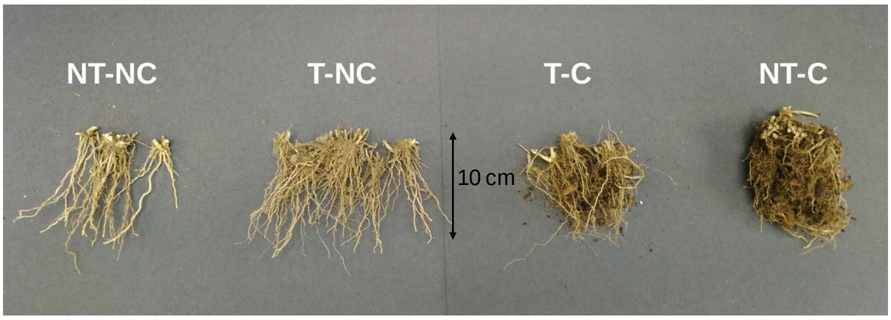

Figure 8. Visual comparison of turfgrass root by land treatments (9 months after hydroseeding).

treatments. The appearance of turfgrass root showed distinct root development by the land treatments (**Figure 8**). The roots from non-compost plots (NT-NC and T-NC) displayed relatively straight roots, while compost-amended plots (T-C and NT-C) appeared to have tangled root development. Note that this is a qualitative, visual comparison and values of dry root mass were not statistically different by the land treatments (**Table 3**).

4. Conclusions

This study investigated the effect of shallow tillage and compost amendment on soil physical and biological properties as well as turfgrass characteristics over a 15-months period in hydroseeded lawn conditions. Compost amendment with and without tillage (NT-C and T-C) showed consistent increase in the IR up to 2 - 3 times compared to the control. The benefits of compost amendment extended to enhancing WAS and soil enzyme (BG) in addition to fostering greener turfgrass and well-aggregated roots in qualitative terms.

Tillage alone (shallow till) was not a significant factor in increasing IR nor reducing BD, while no tillage with compost (NT-C) showed co-benefits of increasing WAS and soil enzyme activity (BG). In this study, compost was applied in two different ways: incorporation of compost with tillage (T-C) and surface application with no tillage (NT-C). Our results demonstrated that both methods were equally effective in improving soil physical properties (BD, IR, and WAS). The soil biological properties (elevated SOM level and BG activity) were further improved in no-tillage scenario. It is important to note that there were previous studies that demonstrated the efficacy of deep tillage in improving IR and turfgrass growth in compacted soils [5] [6] [9]. Our results regarding tillage are limited to shallow tillage under relatively low soil compaction. Where soil compaction is a serious concern for infiltration and vegetation establishment, the combination of deep tillage with compost amendment would be desirable approach.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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