ABSTRACT

ALSHRAAH, SHADDY HISHAM. Soil Tillage for Stormwater Infiltration: Effects of Amendments and Vegetation Type over Time. (Under the Direction of Drs. Richard A. McLaughlin and Joshua L. Heitman).

Urban soils are usually disturbed, compacted, and infertile, resulting in poor vegetation establishment and high runoff rates. Managing stormwater to reduce volumes, peak flows, and pollutant loads is an important goal to minimize the impact on receiving waters. Vegetation is an important element of roadside stormwater control measures (SCMs), as healthy roadside vegetation can reduce erosion and runoff. While grass is the typical vegetation along highways, wildflowers could be planted instead of grass to reduce maintenance and create better pollinator habitat. The potential differences in wildflower species root development on soil properties were explored in a greenhouse study. Soil hydraulic properties were monitored during the root development of two species to quantify the effects of roots development over time on soil pore distribution and hydraulic conductivity. A positive linear correlation between root growth and soil hydraulic conductivity was found under compacted soil conditions. Field-based studies were also established in 2016 in three regions of North Carolina and monitored for 30 months to evaluate the potential improvements in infiltration through the use of tillage together with compost and either grass or wildflowers. Plots planted in wildflowers tended to have higher soil infiltration compared to grass across all sites. Compost application also enhanced the soil infiltration in two sites out of three. Finally, the effect of tractor traffic on soil infiltration resulting from the mowing process was evaluated for wildflowers and grass. Tractor traffic substantially reduced infiltration rates in the wheel tracks but there was some evidence of recovery in the compost-amended wildflower plots. This study demonstrated the ability of compost to improve some soil properties that makes it such a useful amendment for poor urban soils. Also, wildflowers were superior to grass regarding soil infiltration and low maintenance requirements and could be a viable alternative to grass in vegetative stormwater practices.

Soil Tillage for Stormwater Infiltration: Effects of Amendments and Vegetation Type over Time

by
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DEDICATION

To my dear parents, lovely children Adam and Julia, friends, and advisors who supported me throughout my PhD journey.

BIOGRAPHY

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Abstract

Roadside soils are challenging to restore and often infertile, disturbed, and compacted. Vegetation is an essential component for stormwater control measures, (SCM) and hydraulic conductivity (k_h) is a key indicator of their efficiency. Our goal was to quantify the effect of two species of wildflowers, lanceleaf coreopsis (LC; *Coreopsis lanceolate L.)* and Partridge pea (PP; *Chamaecrista fasciculata*) of different root structure (tap and fibrous) on soil hydraulic conductivity (k_h) and pore size distribution under two soil compaction levels. Non-compacted (1.15 $g.cm^{-3}$) and compacted (1.35 $g.cm^{-3}$) soil columns (pots) of sandy loam soil with and without vegetation (control) were tested by minidisk infiltrometer at 40, 80, and 120 days after seeding under three tensions (h) (-6, -3, and -0.5 cm). PP did not develop a significant root mass under either compaction level. LC root mass was higher after 120 days than after 40 days regardless of the compaction level. Neither PP nor LC increased k_h during the growing period under non-compacted soil, and k_h tended to be similar or significantly lower than the control at $h = -0.5$ and $h = -6$ cm for PP and LC, respectively. Only LC roots improved k_3 in the mesoporosity ($0.025 < r < 0.05$ cm) for compacted soil. There was a positive linear correlation between LC root density and k_h at $h = -6$ and -3 cm in the compacted soil. The meso and macroporosity in the planted and control pots tend to decrease with time under the non-compacted pots. Mesoporosity increased with LC root growth in the compacted pots. Results should be validated with more plant species and under field conditions.

1.1 Introduction

Soil infiltration is a critical factor when evaluating the efficiency of highway vegetative stormwater control measures (SCM) methods. Many roadside soils are highly disturbed and poorly structured as they are made up of imported soil “fill” and often lack topsoil (Mohammadshirazi et al., 2017). Moreover, these soils are often compacted by construction and maintenance activities. Therefore, quick and vigorous vegetation establishment is recommended to provide high infiltration rates and minimize post-construction stormwater runoff (Haynes et al., 2013).

Among various factors, vegetation plays a major role in altering the soil structure (Bengough et al., 2012) and soil hydrology (Ng et al., 2014) via roots, which are a key component in plant-related effects on soil hydraulic properties. Plant root penetration into the soil is known to alter the soil pore system (Ehler et al., 1983), which could modify soil structure (Angers & Caron, 1998) and subsequently affect the infiltration rate (Leung et al., 2017). However, contrasting and non-conclusive results have often been reported on the effects of roots on soil hydraulic conductivity. Studies that have reported a decrease in soil infiltration under relatively young plants attributed the decrease primarily to macropore (MCP) clogging by roots under actively growing plants (Barley, 1954; Scanlan & Hinz, 2010; Leung et al., 2015). However, they also reported that decayed roots would create more macropores and enhance the soil hydraulic properties. In contrast, improved soil infiltration has been reported under vegetated soils compared to bare soil (Meek et al., 1992; Vergani & Graf, 2016; Leung et al., 2017), presumably due to development of macropores. Macropores may represent a small portion of the total porosity, but they control the water flow close to saturation, and may be responsible for more than 70% of the total water flow through soils (Watson & Luxmoore, 1986; Wilson &

Luxmoore, 1988). Macropores may be created by either live or decayed roots, which appear to be the most important causes for preferential flow, even if not all the roots are necessarily associated with macropore formation (Perilloet al., 1999).

Root effects on soil hydraulic conductivity depend on the soil type and conditions (e.g. disturbance history) (Mohammadshirazi et al., 2017), vegetation type, root characteristics (Bodner, Leitner, & Kaul, 2014), and scale of measurement (Luxmoore, 1981). Due to the many factors regulating the relationship between root characteristics and soil hydraulic properties, measuring the effect of roots on soil hydraulic conductivity presents a unique challenge. Among a wide range of techniques and devices used to quantify the effects of plant roots on soil hydraulic properties is the disk infiltrometer (Dohnal et al., 2010). Disk infiltrometers are widely used for the determination of soil hydraulic properties (e.g., Zhang, 1997; Ronayne et al., 2012; Zhao et al., 2014) and characterizing water-conducting macro- and mesoporosity in surface soils (e.g., Watson & Luxmoore, 1986; Bodhinayake et al., 2004; Moret & Arrúe, 2007; Soracco et al., 2015). They are constructed to maintain adjustable negative (less than atmospheric) water pressure at the soil surface allowing elimination of flow in macropores larger than a specified pore size (the equivalent pore radius) (Angulo-Jaramillo et al., 2000).

An attractive choice recently available for measuring surface hydraulic properties is the mini-disk infiltrometer (MDI). Minidisk infiltrometers (MDI) have become popular due to their compact size and the small amount of water needed for their operation. The Decagon Devices (Pullman, WA, USA) mini-disk infiltrometer can be set to apply pressure heads from −0.5 to −6 cm at the soil surface (Decagon Devices, 2016). The volume of the water reservoir is about 100 mL. It should be noted that MDI measures hydraulic conductivity in a relatively small area.

Hence, a large number of measurements are required for field monitoring due to the high variability of soil hydraulic properties (Dohnal et al., 2010).

While there is a significant body of knowledge on soil-root interaction and how roots modify the soil hydraulic conductivity and pore system, we recognized two shortcomings: (i) most studies were focused on the roots-soil infiltrating interaction under saturated conditions where macropore flow alone is dominant, masking the contribution of smaller pores when unsaturated condition existed; and (ii) species specific root-soil effects are rarely evaluated under the same soil with different compaction levels.

The objectives of our study were to (i) quantify the effects of two wildflower species with contrasting root systems (tap vs fibrous roots) on soil hydraulic conductivity during early establishment, (ii) determine the effects of actively growing roots on the soil pore system, and (iii) evaluate the effects of soil compaction levels on the soil hydraulic conductivity between and within the selected species.

1.2 Materials and Methods

1.2.1 Theory: Water-Conductive Pores

The relationship between the pore hydraulic radius (r) and the water tension (h) is represented by the capillary rise equation (Hillel, 1980):

$$r = -\frac{2\gamma \cos\vartheta}{\rho_w g h} \cong -\frac{0.15}{h} \qquad h < 0 \qquad (1)$$

where, γ (72.8 g s^{-2} at 20 ^{o}C) is water surface tension, $\vartheta$is the contact angle (assumed to be 0, thus $\cos\vartheta = 1$), g (980 cm s^{-2}) is the acceleration due to gravity, and ρ_w (0.9982 g cm^{-3} at 20 ^{o}C) is the water density. The calculated pore hydraulic radius r represents the maximum water-filled pore size at a specified water tension h. Accordingly, pores with radii smaller than r calculated from Eq. (1) will be full of water and are contributing to water flow under a specific pressure head, while pores with larger radii are not contributing to the water flow (Bodhinayake, et al., 2004).

Applying Poiseuille's law and capillary theory, the water flow through a single pore is calculated by

$$Q\ (r) = \frac{\pi \rho g}{8\ \mu}\ r^4 \qquad (2)$$

Where $\mathrm{Q(r)}$ is the water flow rate ($\mathrm{cm^{-3}\ s^{-1}}$) for a given pore radius r (cm) μ is the dynamic viscosity of water (0.00982 $\mathrm{g\ cm^{-1}\ s^{-1}}$ at 20 ^{o}C). Equation (2) assumes laminar flow, that the specified pores are completely full and not interconnected, and that tortuosity and pore necks are insignificant. Because of these assumptions, the associated pore number is merely an equivalent value, not a true number of pores. This equivalent value, while not completely accurate, can provide a relative estimate for hydraulically active pores (Watson and Luxmoore, 1986; Wilson and Luxmoore, 1988) over small depth increments.

Watson & Luxmoore (1986) calculated the maximum number of water-conducting pores per unit area$\left(\Delta \mathrm{N_{a,b}}\right)$, between two r a and b, $(\ \mathrm{a} \leq \mathrm{b}\ )$ using the difference in the hydraulic conductivity, $\Delta \mathrm{k_{a,b}}$ ($\mathrm{cm\ s^{-1}}$) between two h corresponding to the two r $(\ \mathrm{a, b}\ )$ as

$$\Delta N_{a,b} = \frac{8 \mu \Delta k_{a,b}}{\rho g \pi (a)^4} \qquad a\ \leq b \qquad (3)$$

Likewise, the total effective conducting porosity $\theta_{a,b}$ ($\mathrm{cm^3\ cm^{-3}}$) associated with each pore radii equals the maximum number of water-conducting pores per unit area multiplied by the cross-sectional area of the corresponding pore sizes:

$$\theta_{a,b} = \Delta N_{a,b} \pi (a)^2 \qquad (4)$$

Both $\Delta N_{a,b}$ and $\theta_{a,b}$ represent the maximum values for the interval since they are determined by assuming that pores have the minimum radius for the range of tensions considered.

The k_h values were estimated from the infiltration measurements using the minidisk infiltrometer as discussed later in the hydraulic conductivity test section.

The contribution of pores in a given size range to the total water flow, $k_{\Delta h}(\%)$, was calculated as (Cameira et al., 2003)

$$k_{\Delta h}(\%) = \frac{k_h - k_{h-1}}{k_o} 100 \qquad\qquad h = 1, 2, \dots, n \qquad (5)$$

Where h the correspondent tension, k_h and k_{h-1} are the hydraulic conductivity for two consecutive pressure heads, k_o is the saturated hydraulic conductivity, and n is the performed tension measurement in sequence.

In this study, we defined macropores (MCP) and mesopores (MSP) as those pores that drain between h = -0.5 and -3 cm (Luxmoore, 1981), and between h = -3 and -6 cm (Cameira et al., 2003), respectively. Therefore, the equivalent MCP and MSP radius *r* ranges were between 0.3 and 0.05 cm, and between 0.05 and 0.025 cm, respectively. Pore radius *r* was derived from the capillarity equation (Eq. 1).

1.2.2 Experiment Setup

Cylindrical polyvinyl chloride (PVC) pots (M.A. Industries Incorporated, Peachtree City, GA) with 15 cm diameter and 35 cm height were used in the experiment. Five holes of 1 cm diameter were drilled into the bottom of the pot to allow the drainage of water. Cheesecloth was placed in the bottom of the pot to avoid soil loss during watering and the hydraulic conductivity measurements. Sandy loam fill soil (69% sand, 15% silt, 16% clay) from a construction site near Raleigh, NC was used to fill the pots in increments of 5 cm until the targeted soil thickness (30 cm) and bulk density (1.15 or 1.35 $g.cm^{-3}$) were achieved. For the higher bulk density pots, the soil was manually compacted after each layer was added. The lower bulk density represents a bulk density for a recently tilled soil (loose) while the higher bulk density represents post-tillage settled soil (compacted). For simplicity, we hereafter refer to bulk densities of 1.15 $g.cm^{-3}$ and 1.35 $g.cm^{-3}$ as non-compacted and compacted, respectively.

1.2.3 Selected plants species and growth conditions

Two wildflowers species were tested, lanceleaf coreopsis (*Coreopsis lanceolata*) and partridge pea (*Chamaecrista fasciculate*), which represent two plants with contrasting root systems. The lanceleaf coreopsis (LC) is a perennial species with a fibrous root system, and the partridge pea (PP) is an annual species with a tap root system**.** These species were selected because they are native wildflowers found throughout much of the United States, grow well in disturbed and infertile soils (USDA- NRCS, 2012), and they are listed in the North Carolina roadside wildflowers booklet. They have been planted individually or among wildflowers seed mixes by NCDOT along north Carolina highways (NCDOT, 2012), and were reported individually or collectively in studies or technical manuals related to stormwater practices [i.e., bioretention (Li et al., 2011), green roof (Rowe et al., 2006), and filtration buffer strips (Steinke et al., 2007 and Herringshaw et al., 2010)].

Five seeds were planted directly in each pot to ensure sufficient germination. Seeds were planted on June 6, 2017. After germination, plants were thinned to maintain only one seedling per pot. Pots were kept in a greenhouse (Horticulture Field Lab, College of Agriculture and Life Sciences, North Carolina State University) during the experiment, with an average daily temperature of 29 ^{o}C and relative humidity of 79%. An automatic drip irrigation system was used during the study (1892.7 cm^3 $hour^{-1}$ Rain Bird Emitters, Azusa, CA). Both control (bare soil) and planted pots were watered equally. All pots were watered daily at 3.45 cm day^{-1} for the first two weeks and then decreased to 1.73 cm day^{-1}. After approximately two months, watering rate was further decreased and maintained at 1.21 cm day^{-1} during the remainder of the growing period.

Measurements on plants and soil were made after two growing periods; 40 days and again at either 80 days for the PP or 120 days for the LC. Five replicates for each species plus control (bare soil), each at two bulk density levels, accounting for 60 total pots, were arranged in a completely randomized block design. Control pots were treated the same way as the planted pots. Fertilizer was added and mixed with soil before planting seeds according to North Carolina Department of Transportation wildflower program guidelines (NCDOT, 2012). Five replicates for each condition were measured at each growth period; pots used in the first growth period were not reused.

1.2.4 Hydraulic conductivity test

At the end of each growing period, before the hydraulic conductivity measurement, the effective height of the soil in the pot was measured to account for soil setting and to calculate the bulk density. A minidisk infiltrometer (MDI) was used to estimate the hydraulic conductivity (Decagon Devices Inc. 2012; Vergani and Graf 2016). Zhang's method (Zhang, 1997) was used for estimating the hydraulic conductivity. The van Genuchten parameters are required in the procedure, which are estimated from the soil texture or calculated by fitting laboratory soil water retention data (Dohnal et al., 2010). However, the manual offers a table of 12 soil texture classes developed by Carsel and Parrish (1988) for van Genuchten parameters.

One hydraulic conductivity measurement was taken per pot for both planted and control pots every 40 days at a constant distance from the plant stem (2.5 cm). Hydraulic conductivity measurement at h = -0.5 cm was chosen to represent conditions as close as possible to saturation, followed by hydraulic conductivity measurements at h = -3 and -6 cm, applied in this order to the same area. The effective pore number (Eq. *3*), effective porosity (Eq. *4*), and contribution to the total flow percent Eq. *(5)* were calculated after estimating the hydraulic conductivity rate.

To account for different soil compaction levels due to the soil settling over time and to compare the hydraulic conductivity results at different plant ages, normalized hydraulic conductivity values were used for all tensions by dividing each hydraulic conductivity value by the average of the corresponding control pots (Vergani & Graf, 2016):

$$\mathrm{k}_{\mathrm{norm\ hi}} = \frac{k_{hi}}{\frac{1}{n}\sum_{c=1}^{n} k_{c\ hi}} \qquad (6)$$

where $k_{norm\ hi}$ is the normalized hydraulic conductivity value of a pot at tension h and the time i, k_{hi} is the hydraulic conductivity at tension h time i , $k_{c\ hi}$ is the hydraulic conductivity in the control pots at the same tension and time, and n the number of control pots.

1.2.5 Plants root measurements

After the hydraulic conductivity tests, each species roots were carefully excavated from the pots, washed, and cleaned with water and collected over a 2 mm sieve. Roots were oven dried at 65 ^{o}C for 48 hours, weighed, and used as a plant growth indicator. Root density was then calculated for each species.

1.2.6 Statistical analyses

Analyses of variance (ANOVA) using the PROC GLIMMIX procedure was performed on the dependent variables roots, hydraulic conductivity rates (k_{6}, k_{3}, and $k_{0.05}$), effective porosity (macroporosity and mesoporosity), and flow % (macropore flow and mesopore flow). Normality tests were conducted for all data using the Shapiro-Wilks test, and hydraulic conductivity rates

(k_h) and effective porosity ($\theta_{a,b}$) was log-transformed to yield a normal distribution. Statistical analyses were carried out using SAS 9.4 (SAS, Cary, NC).

The analyses were performed as a split split-plot design with soil cover (planted and control) as main plot, compaction (non-compacted and compacted) as sub-plot, and time (two times for PP and three times for LC) as sub sub-plot. The treatments were replicated five times in a randomized complete block design. Lanceleaf coreopsis and PP hydraulic conductivity rates, effective porosity, and flow data were analyzed separately because LC had longer growing period than PP. Root data were analyzed for each species individually as a split plot design with compaction as main plot and time as sub-plot. Comparisons between means were made using Fisher's least significant (LSD) difference when the F-value in the ANOVA was statistically significant ($P < 0.05$).

1.3 Results and Discussions

1.3.1 Statistical analysis

The analysis of variance (ANOVA) for LC and PP are shown in Tables 1.1 and 1.2, respectively. The statistical analysis revealed a number of significant fixed effects and interactions. For the hydraulic conductivity rates, effective porosity (macroporosity and mesoporosity), and flow contribution % (macropore flow and mesopore flow), mean separation tests were conducted on the cover x compaction x time.

1.3.2 Plant root development

The PP and LC germinated in the pot soil and the root development was relatively uniform throughout the pots, not following the pot sides or accumulating at the bottom. Neither LC nor PP root growth were affected by the level of compaction tested (Fig. 1.1). The root mass for LC after 120 days was higher ($p \leq 0.05$) than at 40 days. However, while PP root growth between 40 and 80 days was considerable, the difference was not significant. The lack of root growth between measurements for PP is likely attributed to the shorter measurement interval (40 days) compared to LC (80 days). Partridge pea began to senesce earlier than LC, and an insect infestation was observed for some PP plants, which is why they were harvested sooner.

1.3.3 Hydraulic conductivity measurements

Partridge pea

Figures 1.2 and 1.3 summarize the geometric means of the soil hydraulic conductivity kh for the non-compacted and compacted soils measured at different tensions (h) and times. Under non-compacted soil with PP, k0.5 ($p \leq 0.05$) and k3 ($p \leq 0.05$) decreased and k_6 tended to decline over time (Fig. 1.2). Comparing kh for PP to the control, only $k_{0.5}$ was lower than the control after 80 days (Fig. 1.2). There was no significant change in k_h for the corresponding control across all tensions at 40 and 80 days (Fig. 1.2).

For the compacted soil, the kh values for PP were relatively lower than the control values at tensions 0.5 and 6 cm, and lower than the control at tension 3 cm ($P \leq 0.05$) throughout the growing period (40 and 80 d). A declining trend was observed for $k_{0.5}$, k_3 remained stable, and k_6 slightly increased in control and PP pots (Fig. 1.3). The results suggested a minimal or even a negative effect on the soil hydraulic properties under PP plant over time during the growing season (80 d). In fact, the PP did not develop a significant increase in root mass from 40 to 80 days which might explain these observations (Fig. 1.1).

Lanceleaf coreopsis

The k_h values for LC with the corresponding control are shown in Figures 1.4 and 1.5, respectively. For the non-compacted soil planted with LC, a similar pattern was observed where k_h tended to decline with time across all tensions (Fig. 1.4). The reduction in k_h was only significant for h=6 cm after 120 days. No changes in the corresponding control for k_h across all tensions over time except at h= 0.5 cm. Comparing LC to the control k_h values, only k_6 for LC was lower than the control after 80 and also after 120 days ($P \leq 0.01$) (Fig. 1.4c).

An opposite pattern was identified for the compacted soil where k_h values tend to increase with time in the planted pots while they tended to decline or remained stable in the control pots across all tensions (Fig. 1.5). After 40 and 80 days, the difference between k_h values for LC and the corresponding control pots across all tensions were not significant. The final experimental run (120 d), showed an increase in k_3 for LC planted pots ($P \leq 0.05$) and k_3 was higher than the corresponding control pots (Fig. 1.5b), which might indicate an interaction between plant growth represented by root biomass and the pore size distribution change (discussed later).

Soil reconsolidation or settling was likely responsible for decreasing the k_h values in the non-compacted pots for PP and LC as a result of watering, gravity, and the rearrangement of the soil particles. Similar trends were observed in another study (Vergani & Graf, 2016). To quantify soil settling, we calculated a settling index of the soil for the non-compacted and compacted pots by measuring the difference between the initial soil height (I_i) and the soil height at each corresponding hydraulic conductivity measurement (I_{i+1}) Eq. 7:

$$Settling\ index, \% = \frac{I_i - I_{i+1}}{I_i} \times 100 \qquad (7)$$

The larger the percentage, the more the soil is settled (Figure 1.6). This settling index can be used as a proxy for soil compaction over time. The average settling for the NC pots was 3% and less than 1% for the C pots.

1.3.4 Effective water-conducting pores and porosity

The effective meso- and macroporosity for LC and PP are presented in Figures 1.7 and 1.8. The compaction level adversely impacted the meso- and macroporosity and was prominent 40 days after the planting date. The values for meso- and macroporosity in the compacted pots were lower by approximately one order of magnitude in the macropores and more than one order of magnitude in the mesopores range.

Partridge pea

For the non-compacted soil, the meso and macroporosity after 80 days were lower than at 40 days ($P \leq 0.05$), but only mesopore was different from the control pots at 80 days ($P \leq 0.05$). No significant changes for meso and macroporosity were observed in control pots (Fig. 1.7).

For the compacted soil, the mesoporosity did not change for the control and PP throughout the treatment time. While the macroporosity decreased ($P \leq 0.05$) after 80 days, however, it was not different from the control pots (Fig. 1.7).

Lanceleaf coreopsis

For the non-compacted soil, the meso and macroporosity in the LC pots did not decrease with time, however, the macroporosity slightly increased after 120 day compared to the 80 days values and relatively higher than the control but remained lower than the initial values (40 day) (Fig. 1.8).The reduction in the meso and macroporosity is likely due to soil settling (Fig. 1.4) and by pore clogging by roots in the LC (discussed later) pots since there was a noticeable increase in the root biomass at 120 days (Fig. 1.1).

For the compacted soil pots, the macroporosity did not change for the control and LC throughout the treatment time. The mesoporosity increased in the LC pots and was higher than the control pots at 120 days ($P \leq 0.05$), a reversal from the 40 days measurement (Fig. 1.8). This increment in mesopores was reflected in k_3 where it increased with time and was higher than the control k_h values (Fig. 1.5).

The low values of macroporosity and mesoporosity found in the present study are consistent with others reported in the literature (Watson & Luxmoore, 1986; Cameira et al., 2003; Moret & Arrúe, 2007). Although both macro and mesoporosity compromise a tiny fraction of the total porosity, they were responsible for approximately 80% of the flow in all treatments. For the noncompacted pots, after 40 days, 80% of the flow occurred through the macropores ($0.3 > r > 0.05$ cm) in the planted and control pots and did not decrease after 80 and 120 days in the PP and LC, respectively (Figs. 1.9 and 1.10). However, the mesopores flow decreased in the control pots to approximately 60% after 120 days. Similar trends for the macropores flow contribution were observed in the compacted pots with a slight reduction in the planted pots. The contribution of mesopores ($0.05 > r > 0.025$ cm) did not have significant changes with time under the noncompacted soil in control and planted pots. In contrast, under the compacted soil, the contribution of mesopores increased with time for the planted pots and increased from 6.4 to 17% after 120 days in the LC pots (Fig. 1.10). While the mesopore flow decreased after 120 days from 16.2 to 3.2% for the control pots.

1.3.5 Effects of roots on soil infiltrability

The normalized hydraulic conductivity, $k_{norm\ hi}$, values for the LC and PP are presented in Figure 1.11. The $k_{norm\ hi}$ values across all tensions for PP after 80 days were lower than the control pots in the noncompacted and compacted pots. A similar trend was observed for the LC in the noncompacted pots except for the $k_{norm\ hi}$ under tension -0.5 cm. In contrast, under the compacted soil, the $k_{norm\ hi}$ values for the LC increased with time and were higher than the values in the control pots after 120 days.

The PP did not develop a significant amount of root mass over time (Fig. 1.1). Therefore, we could not find a relationship between root density and hydraulic conductivity at all tensions. In contrast, for the LC planted pots, we were able to establish a linear relationship between the root density and the $k_{\text{norm hi}}$ values at specific tension heads under the compacted and noncompacted pots (Figs. 1.12 and 1.13). We were not able to find a relationship between the $k_{\text{norm 0.5}}$ and the root density, however, a positive linear relationship can be establish between the LC root density and $k_{\text{norm 6}}$ and $k_{\text{norm 3}}$ with $R^2 = 0.59$ (p-value =0.009) and 0.55 (p-value =0.014), respectively (Fig. 1.12). On the other hand, under the non-compacted conditions, the only significant negative linear relationship was identified for the $k_{\text{norm 6}}$ and root density (Fig. 1.13). No relationships between the $k_{\text{norm 0.5}}$ and $k_{\text{norm 3}}$ and the root density were identified (data are not shown).

Our results show contrasting effects of root growth on soil hydraulic conductivity. Under the noncompacted soil condition, we found a reduction of hydraulic conductivity at all tensions over time and relatively lower conductivity than for the control. In contrast, the hydraulic conductivity increased with plant growth under the compacted conditions when the root growth was significant over time, particularly under the LC treatment. Several contrasting observations were reported in different studies that focus on relatively young plants to quantify the relationship between the active root growth and soil hydraulic properties. For example, Leung et al. (2015) reported a lower hydraulic conductivity under vegetated soil (grass) than bare soil and found the difference of hydraulic conductivity between the vegetated and bare soil could be as large as 100% at the beginning of testing. Another study reported a reduction in hydraulic conductivity by 40% after two months of growth under cotton (Meek et al., 1990). On the other hand, Leung et al. (2017) found increased hydraulic conductivity induced by root growth by up to an order of magnitude compared with bare soil during early plant establishment.

The nature of the relationship between the hydraulic conductivity and root growth appeared to be controlled by both soil conditions and root characteristics. There could be two different mechanisms induced by root growth. Under the noncompacted (loose) soil, in addition to soil settling, we hypothesized a temporal pore-clogging mechanism (Morgan et al., 1995) or division of the larger pores into smaller pores due to root growth into existing pores (Scanlan & Hinz, 2010). In compacted soil, a biological drilling mechanism by the root growth has been proposed, and penetrating the soil matrix can cause enlargement of existing pores while compressing adjacent soil pores (Cresswell & Kirkegaard, 1995; Bengough, 2012). During soil penetration, roots exert axial and radial pressures, pushing aside soil particles creating a continuous pore system and channels that affect hydraulic conductivity.

In our study, the soil was extremely disturbed and structureless, particularly under the compacted condition due to the preparation steps (excavation, sieving, and compacting), leaving the soil with minimal existence of fast draining pores (meso and macropores) or even disconnected pores. Therefore, introducing plants to such soils may ameliorate the soil pore system, enhancing hydraulic properties and conditioning the soil for subsequent plants.

It was expected that hydraulic conductivity in the compacted soil would increase under the PP due its coarser roots system that would increase the macroporosity, as compared to the LC with a dense, finer root system that might decrease the macropores volume by occupying more space in the macropores range. The shallow PP observed roots in our experiment probably had limited effectiveness in the pots. The deeper LC roots may have been able to alter the soil pore distribution by increasing the mesoporosity volume and creating interconnected root channels, as was reflected in the hydraulic conductivity at the end of the experiment. This highlights the capacity of the root system to improve soil hydraulic properties during a short period in compacted soils. The increase in hydraulic conductivity was more prominent under lower tensions (unsaturated conditions) within the mesopore range.

Despite the considerable role of the macropore flow in soil saturated hydraulic conductivity, it is important to note that the nature of the rainfall events is often of a low intensity, and the soil surface may remain unsaturated and pre-ponding conditions can prevail for considerable periods. Therefore, mesopore flow becomes crucial in infiltrating stormwater and therefore, reducing runoff and erosion.

1.4 Conclusion

The objective of this study was to quantify the effects of root growth and development on soil hydraulic conductivity and pore size distribution during early plant colonization under different levels of soil compaction. The compaction level did not affect the root growth of PP and LC, but the LC developed more root biomass than PP. Our findings showed that the magnitude of the change in measured soil hydraulic properties depends primarily on root biomass rather than root type or the initial soil conditions. Both PP and LC roots (tap and fibrous roots) had a negative influence on the hydraulic conductivity values at different tensions when the soil was not compacted. A negative correlation was identified between the LC root density and hydraulic conductivity values in non-compacted soil. In contrast, the LC roots increased the hydraulic conductivity in the mesopore range ($-6 < r < -3$ cm) under the compacted soil with time. A positive linear correlation was established between the LC root density and hydraulic conductivity at tensions -6 and -3 cm. The meso and macroporosity in the planted and control pots tend to decrease with time under the non-compacted conditions. Mesoporosity increased with LC root growth. Our results should be validated by extending the research to the field scale, taking into account the complexity of the soil and the environmental systems. Furthermore, other plant species with different roots traits can be used starting with greenhouse experiments and then extended to the field scale. The findings confirmed the importance of the early establishment of vegetation cover in disturbed soils in respect of improving soil hydraulic properties and therefore, reducing runoff and erosion.

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Tables and Figures

Table 1.1. Analysis of variance (ANOVA) for the Lanceleaf coreopsis

Source of variation	K_6	K_3	$K_{0.5}$	Macroporosity	Mesoporosity	Macro flow	Meso flow
Cover	*	*	NS	NS	NS	NS	NS
Compaction	**	***	***	***	***	NS	NS
Cover x Compaction	NS	NS	NS	NS	NS	NS	NS
Time	NS	NS	†	*	NS	†	NS
Cover x time	NS	NS	NS	NS	NS	NS	*
Compaction x time	NS	NS	NS	NS	NS	NS	NS
Cover x compaction x time	*	*	NS	NS	*	NS	*

†, *, **, and *** indicate significant p-values for α = 0.1, = 0.05, = 0.01 and = 0.001, respectively.

Table 1.2. Analysis of variance (ANOVA) for the Partridge pea.

Source of variation	K_6	K_3	$K_{0.5}$	Macroporosity	Mesoporosity	Macro flow	Meso flow
Cover	NS	*	NS	NS	*	NS	NS
Compaction	**	***	***	***	***	NS	NS
Cover x Compaction	NS	†	NS	NS	NS	NS	NS
Time	NS	†	**	**	**	*	*
Cover x time	NS	†	*	†	NS	NS	NS
Compaction x time	NS	NS	NS	NS	NS	*	NS
Cover x compaction x time	NS	*	*	†	*	NS	NS

†, *, **, and *** indicate significant p-values for α = 0.1, = 0.05, = 0.01 and = 0.001, respectively.

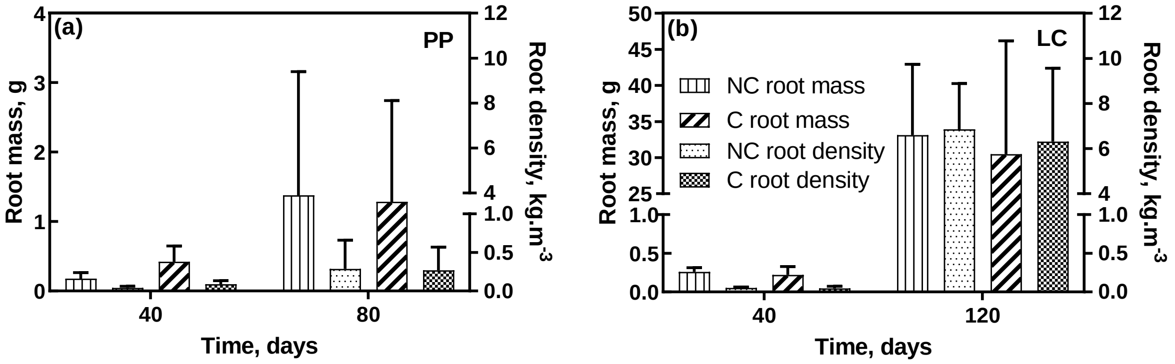

Figure 1.1. Root mass and root density for (a) partridge pea (PP), and (b) lanceleaf coreopsis (CL) under non-compacted (NC) and compacted (C) conditions. Bars indicate the standard error.

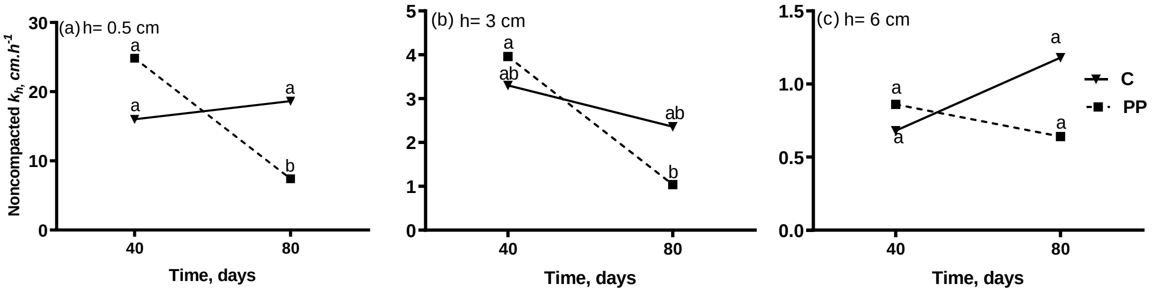

Figure 1.2. Hydraulic conductivity over time for the control (C) and Partridge pea (PP) under non-compacted soil at tensions (h) (a) h= 0.5 cm, (b) h= 3 cm, and (c) h= 6 cm. Significant differences ($p < 0.05$) are indicated if values do not share a letter.

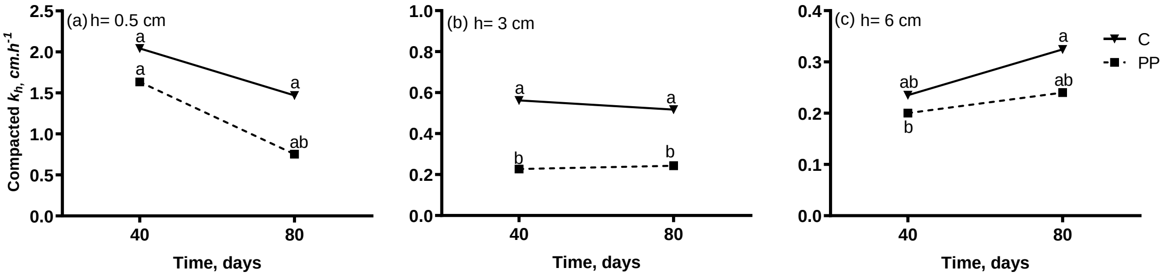

Figure 1.3. Hydraulic conductivity over time for the control (C) and Partridge pea (PP) under compacted soil at tensions (h) (a) h= 0.5 cm, (b) h= 3 cm, and (c) h= 6 cm. Symbols with different letter in a column differ at P ≤ 0.05.

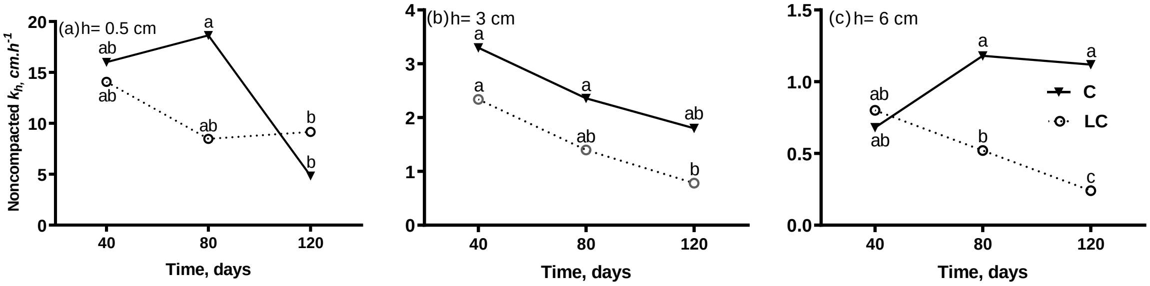

Figure 1.4. Hydraulic conductivity over time for the control (C) and Lanceleaf coreopsis (LC) under non-compacted soil at tensions (h) (a) h= 0.5 cm, (b) h= 3 cm, and (c) h= 6 cm. Symbols with different letter in a column differ at P ≤ 0.05.

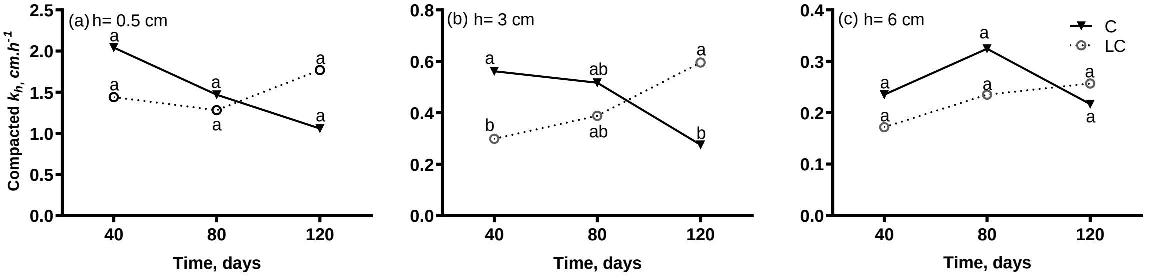

Figure 1.5. Hydraulic conductivity over time for the control (C) and Lanceleaf coreopsis (LC) under compacted soil at tensions (h) (a) h= 0.5 cm, (b) h= 3 cm, and (c) h= 6 cm. Symbols with different letter in a column differ at P ≤ 0.05.

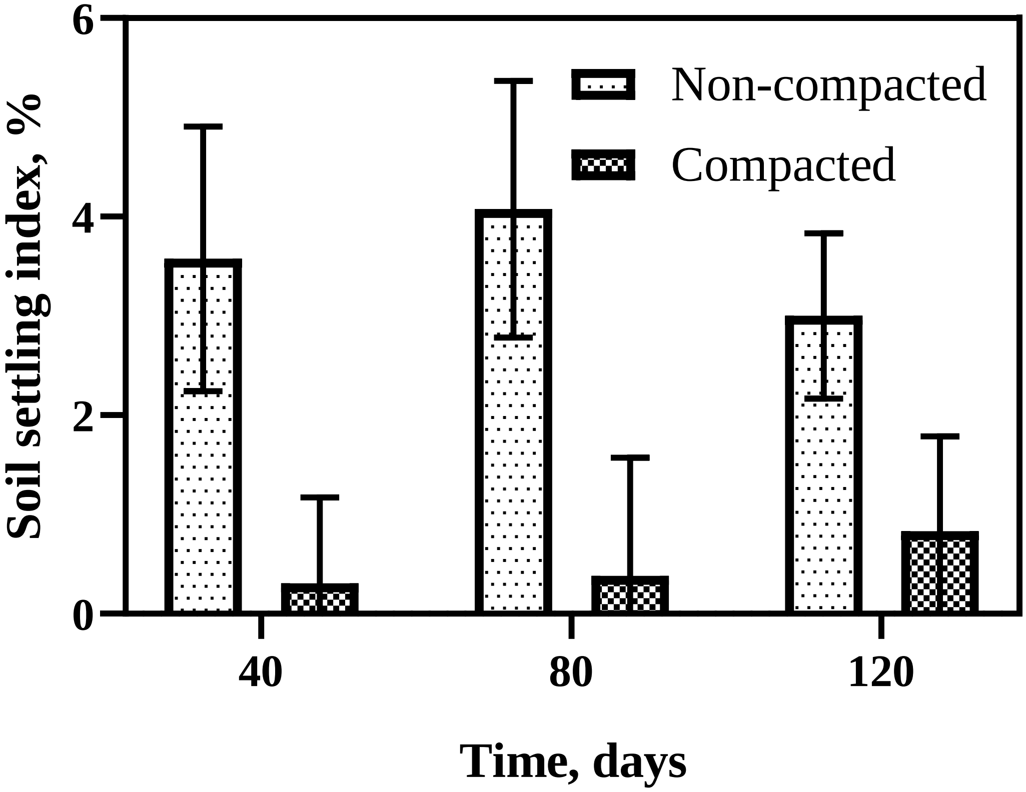

Figure 1.6. Soil settling index with time for non-compacted and compacted soil. Bars represent standard deviation.

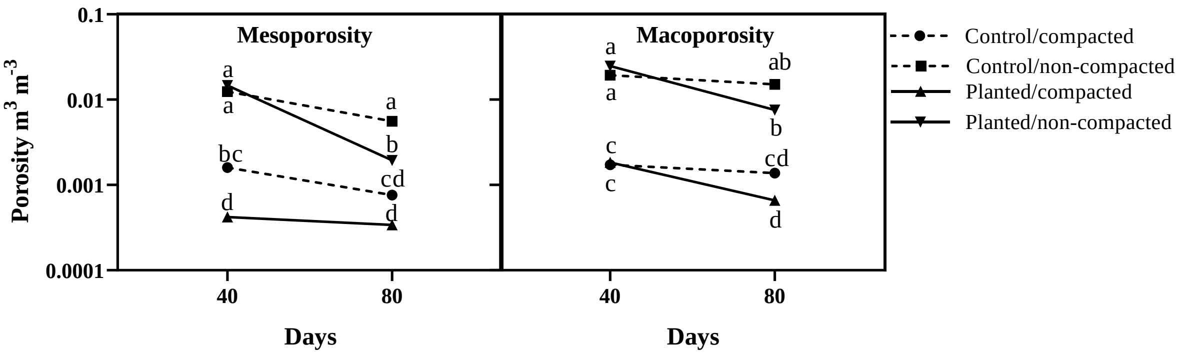

Figure 1.7. Effective mesoporosity and macroporosity for partridge pea. Symbols with different letter in a column differ at P ≤ 0.05

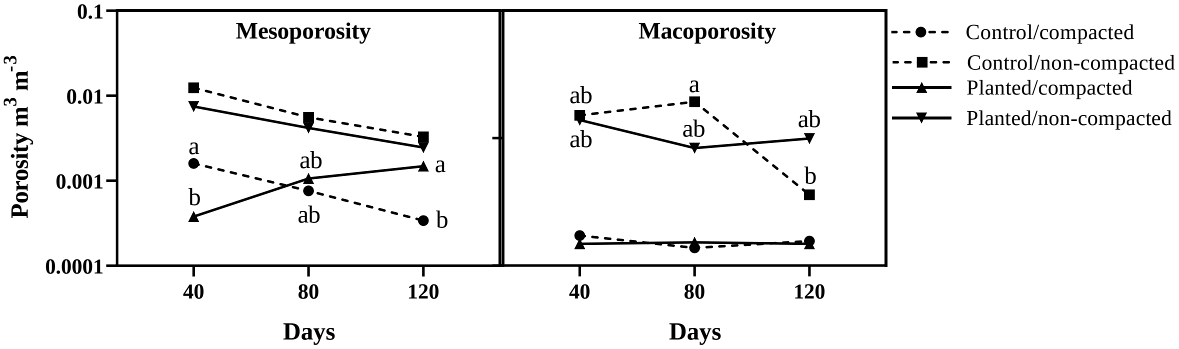

Figure 1.8. Effective mesoporosity and macroporosity for lanceleafe coreopsis. Symbols with different letter in a column differ at P ≤ 0.05

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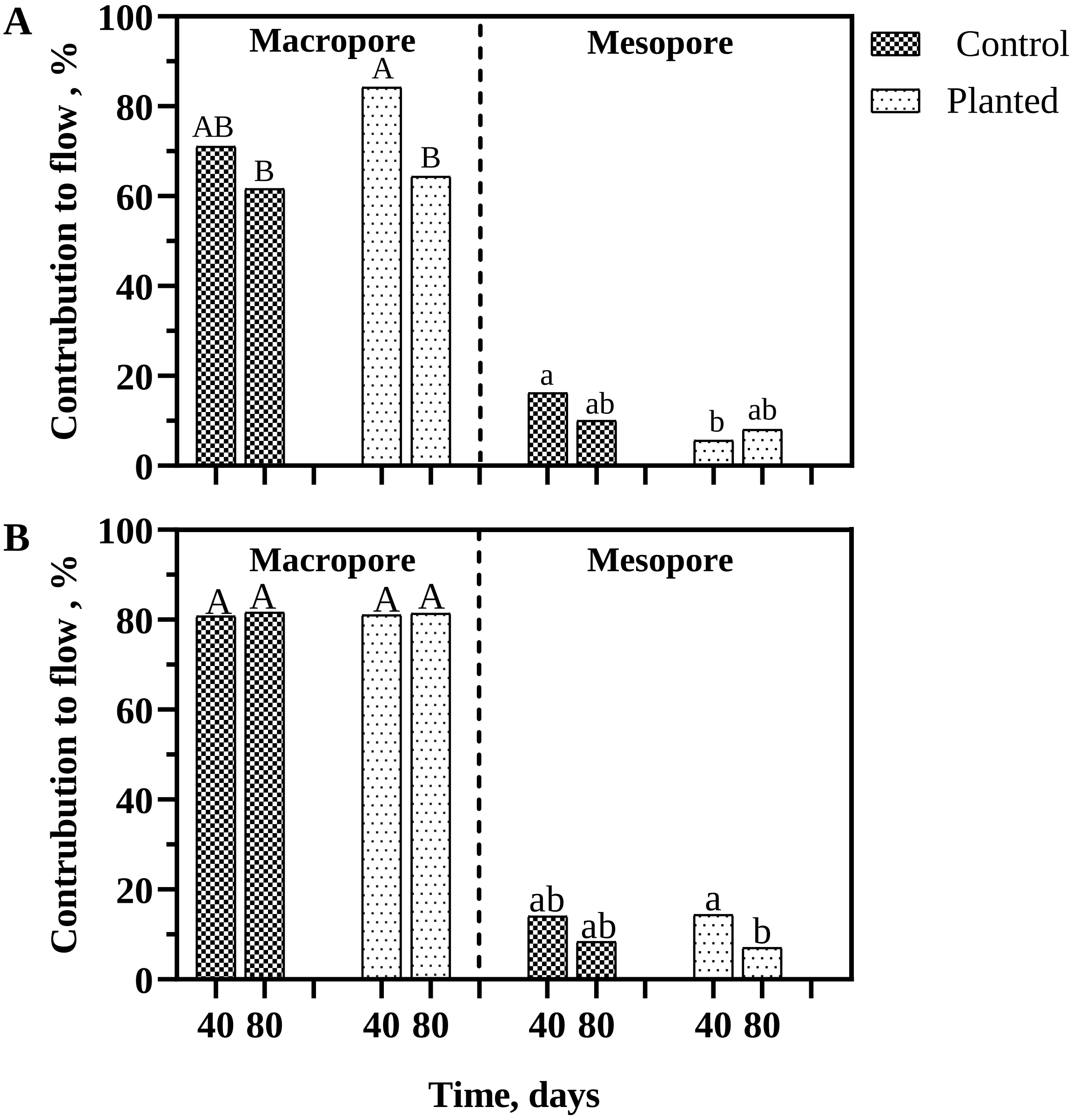

Figure 1.9. Partridge pea macro and mesopores contribution to the total flow (%) for (A) non-compacted soil and (B) compacted soil. Capital letters refer to macropore flow and small letters to mesopore flow in comparison to the control. Symbols with different letter differ at $P \leq 0.05$.

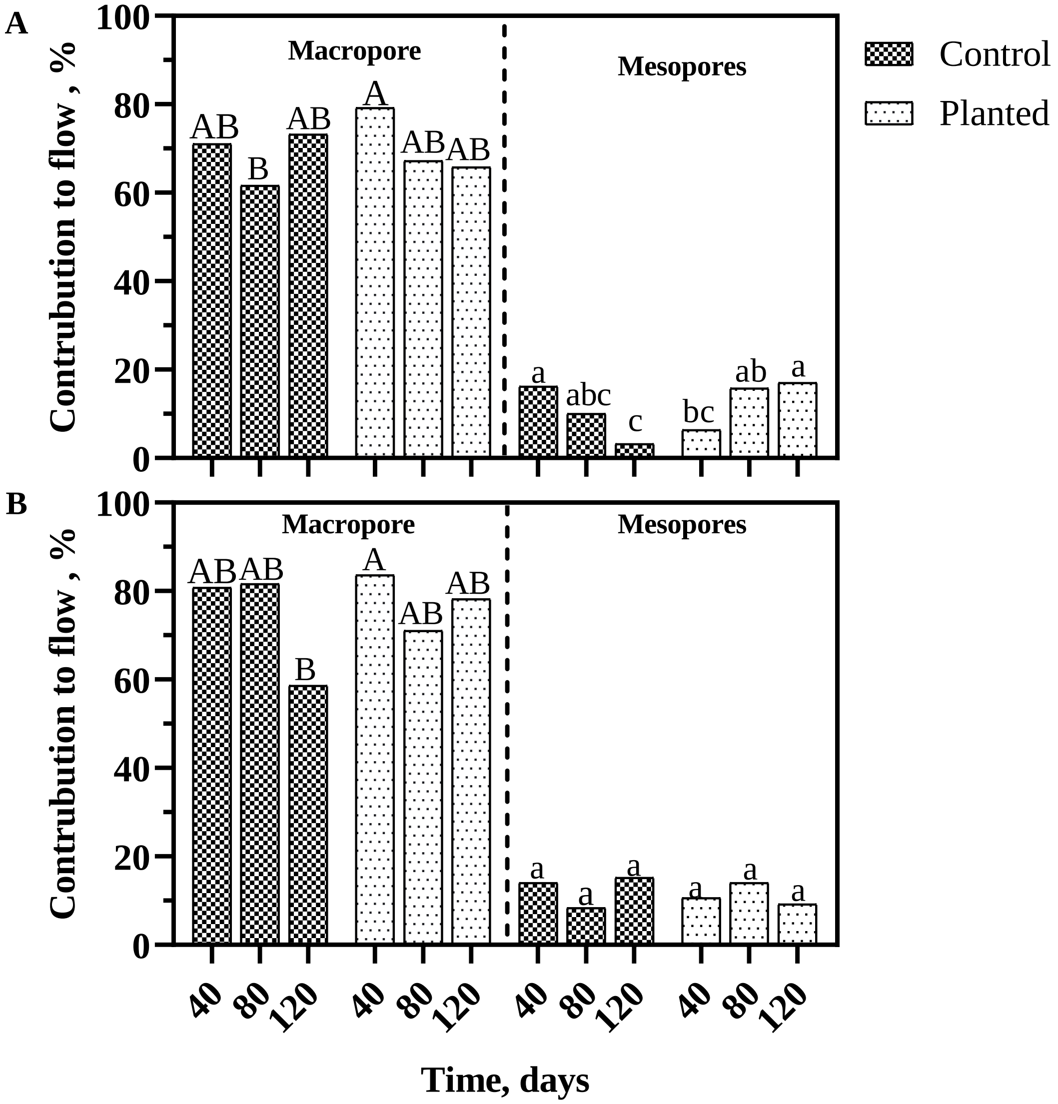

Figure 1.10. Lanceleaf coreopsis macro and mesopores contribution to the total flow (%) for (A) compacted soil and (B) non-compacted soil. Capital letters refer to macropore flow and small letters to mesopore flow in comparison to the control. Symbols with different letter differ at P ≤ 0.05.

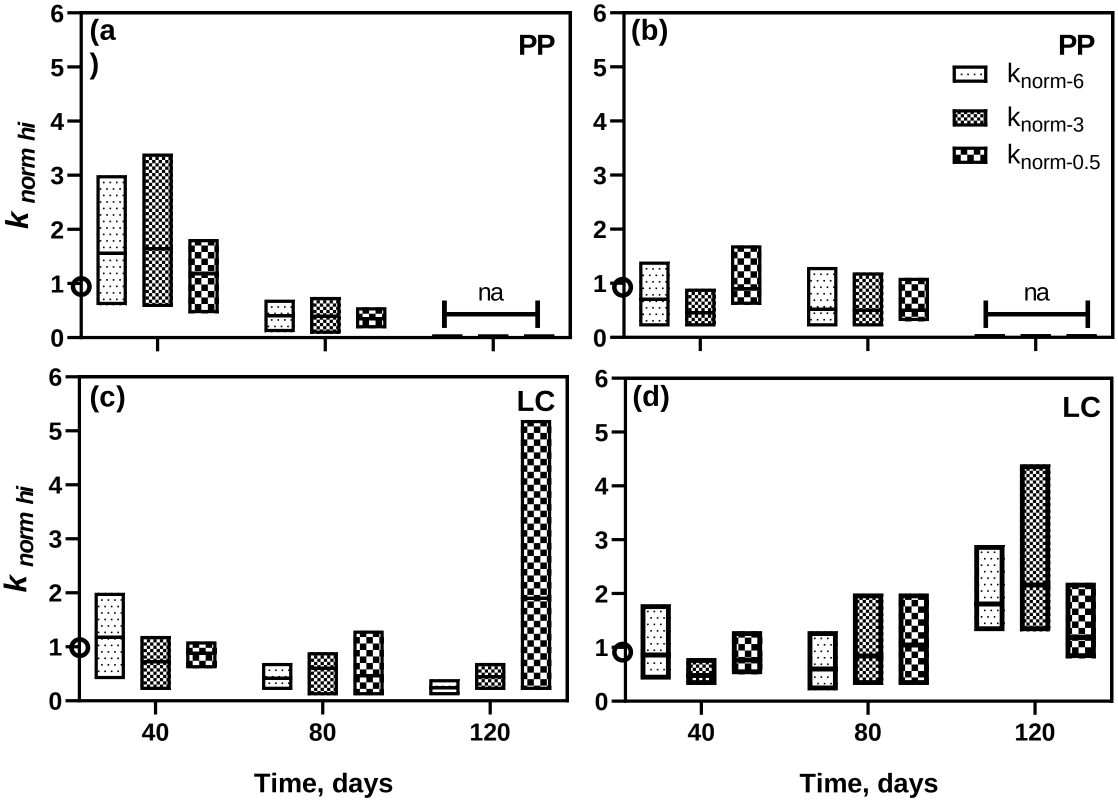

Figure 1.11. Normalized k at tensions (-6, -3, and -0.5 cm) for (a) partridge pea (PP) / non-compacted soil, (b) partridge pea / compacted, (c) lanceleaf coreopsis (LC) / non-compacted, and (d) lanceleaf coreopsis / compacted soil over time.

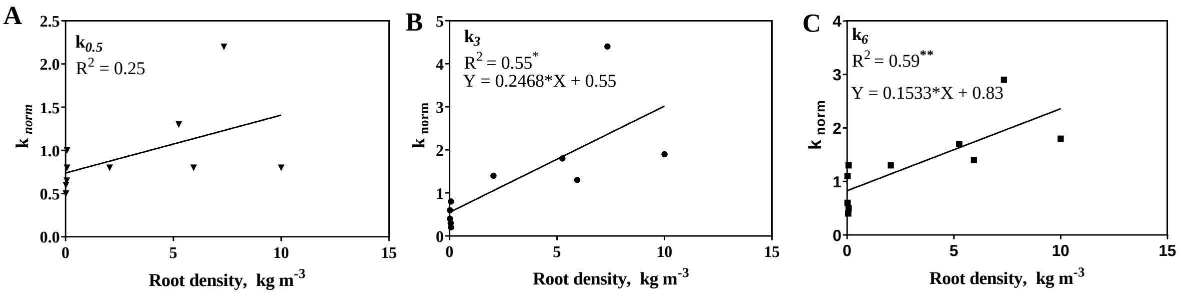

Figure 1.12. Linear relationship between the lanceleaf coreopsis (LC) root density and the normalized hydraulic conductivity (k_{nrom}) for the tensions (A) -0.5, (B) -3, and (C) -6 cm under the compacted soil. Single asterisk indicates significance level ($P < 0.05$) and double asterisk indicates a significance level ($P < 0.01$).

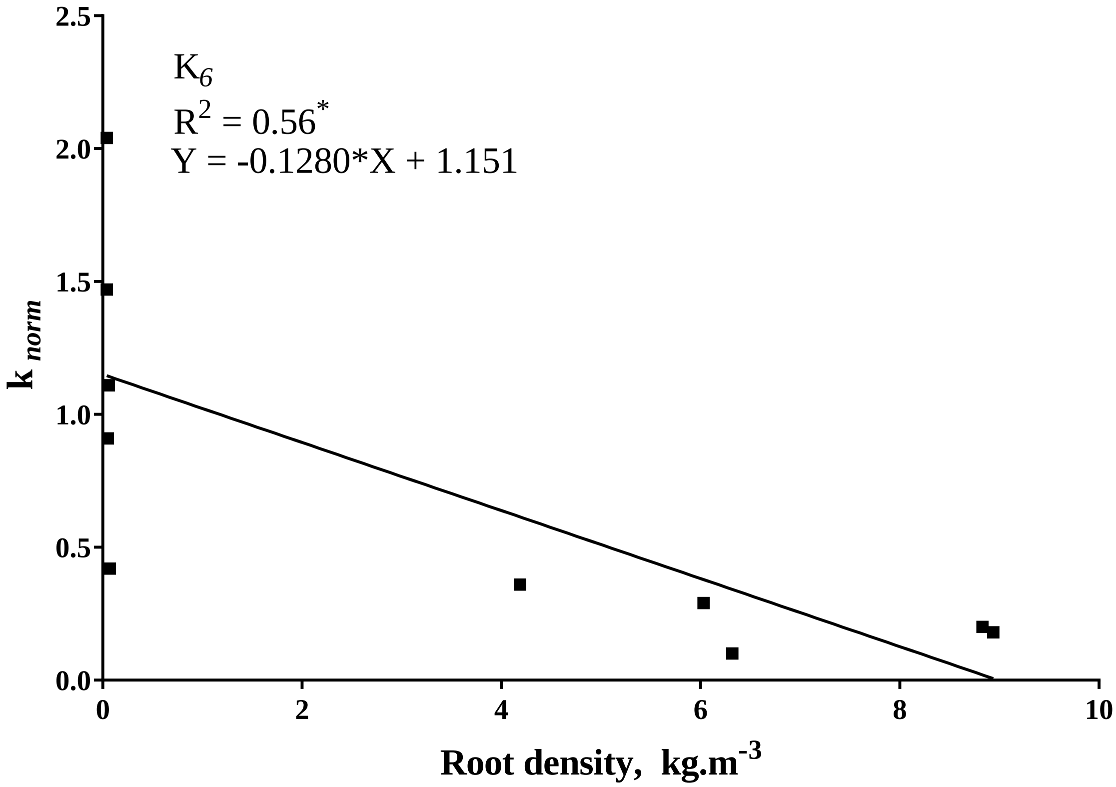

Figure 1.13. Linear relationship between the lanceleaf coreopsis (LC) root density and the normalized hydraulic conductivity (k_{nrom}) at tensions -6 cm under the non-compacted soil. Single asterisk indicates a significance level ($P < 0.05$).

Chapter 2: Effect of Vegetation Type and Compost Amendment on Disturbed Soil Properties over Time

Abstract

Urban soils are usually disturbed, compacted, and infertile, resulting in poor vegetation establishment and high runoff rates. Managing stormwater to reduce volumes, peak flows, and pollutant loads is an important goal to minimize the impact on receiving waters. Vegetation is an important element of roadside stormwater control measures, as healthy roadside vegetation can reduce erosion and runoff. While grass is the typical vegetation along highways, wildflowers could be planted instead to reduce maintenance and improve pollinator habitat. Previous studies have established that tillage followed by establishment of a vigorous stand of vegetation can greatly increase infiltration relative to compacted soils. The main goal of this study was to evaluate the potential improvements in infiltration through the use of tillage together with compost and either grass or wildflowers over 30 months. Wildflowers or grass were planted on tilled soil (15 cm) with or without compost in the Coastal Plain (CP), Piedmont (PD), and the Mountain (MT) regions of North Carolina. Bulk density (BD), infiltration rate (IR), root mass density (RMD,) and soil penetration resistance (PR) were measured every six months over a 30-month period. Compost application reduced soil BD compared to tillage alone across all sites throughout the experiment period. Compost improved IR by about 50 and 46% at the PD and MT sites, respectively. Wildflowers improved IR by 43, 41, and 30% for the CP, PD, and MT, respectively, compared to grass. In most cases, neither compost nor vegetation type affected the RMD within the tillage depth. Almost 90% of the roots were found to be within the topmost 15

cm depth (tillage depth). Results suggest that compost and/or wildflowers in addition to tillage seem to be suitable options to improve BD and increase infiltration in areas with disturbed soil.

2.1 Introduction

Urban stormwater runoff often contains a wide variety of sediments and pollutants generated from transportation and non-transportation activities (Kayhanian et al., 2019), and runoff from impervious highways can degrade environmental conditions in adjacent waterbodies (Walsh et al., 2005). Management of stormwater runoff from highways is an essential and integral component of highway design (NCDOT, 2015), and transportation agencies are always searching for cost-effective, efficient, and low-maintenance methods to manage and treat stormwater runoff and meet regulatory requirements (Henderson et al., 2016).

Roadside vegetation plays a critical role in decreasing runoff and associated pollutants by improving the soil hydraulic conditions. Vegetation improves soil function by increasing infiltration, which reduces runoff volumes and pollutant concentrations in runoff (Popov et al., 2006). Therefore a vigorous vegetation stand is critical to maintain high infiltration when managing urban soils to reduce runoff volumes from paved highways (Haynes et al., 2013). During road construction, roadside soils are disturbed, excavated or graded, and compacted. In many cases, the existing topsoil is totally removed, reducing soil quality and fertility, and limiting future plant establishment (Risse and Faucette, 2009; Mohammadshirazi et al., 2017). As a result, conditioning the soil prior to vegetation establishment is essential to improve soil physical properties and plant growth. From agricultural tillage studies (Meek et al., 1992) to reforestation (Greenwood & Buttle, 2014) and mine soil reclamation (Gao-Lin et al., 2016) projects, soil conditioning practices are increasingly recognized as essential tools to restore landscapes environmental services altered by human activities.

Tillage can be used to improve the physical properties of compacted soils. Primarily, tillage loosens the soil surface by breaking the massive structures, thus increasing soil pore space and allowing water to infiltrate and roots to penetrate through the soil profile (Loper et al., 2010).

Additionally, organic additions to soil have long been considered important in maintaining the quality of both natural and managed soils (Adugna, 2016). The addition of organic amendments such as compost or manure to soils can help to stabilize soil structure (Thomas et al., 1996), improve soil physical (Aggelides & Londra, 2000) and chemical properties (Loper et al., 2010), and enhance plant growth (Cogger, 2005). Tillage and compost were reported individually or together in experimental field plots that have been constructed to simulate construction sites and residential landscapes, and they were found to be effective in increasing infiltration rate in actual or simulated construction sites (Haynes et al., 2013; Olson et al., 2013; Mohammadshirazi et al., 2017) .

Grass is the dominant groundcover used in roadside areas. It is generally planted for rapid growth, soil stabilization, erosion prevention and to provide a perennial and year-round landscape. However, over the last few decade, many responsible agencies have sought to incorporate wildflowers into new roadside plantings to achieve alternative management objectives (Hopwood et al., 2015). North Carolina Department of Transportation (NCDOT) has incorporated wildflowers in roadside areas since 1985 as part of highway beautification programs (NCDOT, 2012). Wildflower meadows provide ecological, economical, and aesthetic benefits (Ahern et al., 1992) and offer ecosystem services to local plant populations in terms of climate regulation, pollination, and improvement in soil and air quality (Aldrich, 2002; Norcini & Aldrich, 2004).

Despite the amount of literature that exists on the subject of wildflowers integration into urban and roadside areas, no studies have yet quantified the impact of wildflowers on stormwater infiltration compared to grasses. We conducted field experiments for 30 months in three different locations at North Carolina representing Coastal Plain, Piedmont, and Mountain geographic regions to evaluate the potential improvements in infiltration through the use of tillage together with compost and either grass or wildflowers. The bulk density, infiltration rate, and root mass density and distribution were evaluated to (i) quantify the potential improvements in infiltration through the use of tillage alone or together with compost, and (ii) evaluate the use of wildflowers as an alternative vegetation to grass in stormwater infiltration zones.

2.2 Materials and Methods

2.2.1 Sites description and preparation

Field plots were constructed at three sites in North Carolina representing Coastal Plain (CP), Piedmont (PD), and Mountain (MT) geographic regions of North Carolina. Experiments were located at the Central Crops Research Station (Clayton), Lake Wheeler Road Field Laboratory (Raleigh), and Mountain Horticulture Crops Research Station (Mills River), respectively. The sites mapped as Cecil (Fine, kaolinitic, thermic Typic Kanhapludults), Wagram (Loamy, kaolinitic, thermic Arenic Kandiudults), and Bradson (Clayey, parasesquic, mesic Typic Hapludults) for CP, PD, and MT sites, respectively (Soil Survey Staff, 2016). Composite soil samples (0 – 15 cm depth) were collected from each site for surface soil texture analysis. The soil texture was determined using a hydrometer method (Gee and Bauder, 1983) and ranged from clay loam to sandy clay loam (Table 2.1). Plot preparation at all sites was similar. Coastal Plain, PD, and MT plots were established in fall 2016 on 7, 25, and 25 October, respectively. Existing vegetation was incorporated by tilling the soil to approximately 15 cm depth using a rotary tiller. At the MT site only, a backhoe was used to loosen the soil first before tillage

2.2.2 Treatments

Experimental treatments consisted of 2 x 2 factorial of vegetation type and soil amendment. The vegetation covers were grass or wildflowers and amendments were with or without compost across all sites, resulting in four treatments: (1) grass without compost (G), (2) grass with compost (GC), (3) wildflowers without compost (W), and (4) wildflowers with compost (WC). The source of the compost was McGill Environmental Systems (New Hill, NC) sold by American Soil and Mulch (Cary, NC). The specific product used in this study was Merry Oaks Soil Builder which is manufactured from a wide variety of blended feedstocks.

Two grass mixtures were chosen from the NCDOT seeding and mulching manual, namely (a) east, and (b) west mixes (NCDOT 2016). The east mix included tall fescue (*Festuca arundinacea*) and bermudagrass (*Cynodon dactylon*), seeded at the CL site, while both PD and MT sites were seeded with the west mix which was made up of tall fescue, Kentucky bluegrass (*Poa pretensis*), hard fescue (*Festuca brevipila*), and rye (*Secale cereal*). A pollinator wildflower seed mix of 10 annuals and 7 perennials (Table 2.2) was initially seeded in Fall 2016. The wildflower plots were over-seeded with crimson clover (*Trifolium incarnatum*) and a southeast wildflower seed mix of 15 annuals and 11 perennials and biennials (Table 2.3) from American Meadows, Inc. (Shelburne, Vermont) in Fall 2017 and 2018 after mowing, as the original mix was no longer available. Treatments were organized in a 2 x 2 factorial randomized complete block design with four replications.

2.2.3 Plot setup

Plots were 6.1 x 3 m at CL and PD and 4.6 x 3 m at MT (due to limited available area at MT), with a 0.6 m width alley in the middle of each plot for plot accessibility and mowing operations. Prior to seeding, plots were amended with a granular fertilizer (10-20-20; 560 kg ha^{-1}) and lime (4,480 kg ha^{-1}) according to NCDOT recommendations for roadway areas. Compost was applied to the designated plots at a rate of 300 Mg ha^{-1}, equivalent to 5 cm depth at estimated 600 kg m^{-3} density (Ginkel et al,. 1999). Plots were re-tilled by a rotary tiller for incorporation. Next, grass and wildflowers seed mixtures were sown by hand at application rates recommended by NCDOT (grass) and American Meadows (wildflowers). Amendments and seed application rates are listed in Table 2.4. After seeding, plots were covered with excelsior matting anchored with metal sod staples.

Grass plots were mowed four to five times each year at 15 cm mowing height. Wildflower plots were mowed once each year at 15 cm in late November. A rotary cutter (Bush Hog) attached to a tractor was used in a controlled mowing pattern where two tractor wheels went down the middle of the plots and the other wheels between the plots.

2.2.4 Measured parameters

Before taking measurements, each plot was subdivided into 12 subplots (90 X 120 cm) where all measurements were conducted within the same subplot at a given sampling time, and this location was not used again for subsequent sampling times. Infiltration (IR), bulk density (BD), penetration resistance (PR), and root mass density (RMD) were measured every six months for a period of 30 months (five sample dates). The measurements started 6 months after plots establishment (October 2016). One measurement was taken per plot for each parameter at each sampling time. Measurements were conducted in May and November in 2017, 2018, and 2019, representing spring and fall growing seasons.

2.2.5 Infiltration rate

Constant head infiltration measurements were taken using a single ring infiltrometer consisting of a reservoir 150 cm high, with inner diameter of 10 cm connected to a metal ring with 11 cm diameter. The ring was gently driven into the ground to depth of 7.5 cm. A thin layer of gravel was placed on the soil surface to minimize disturbance at the beginning of the infiltration process. A pressure head of 5 cm was established at the soil surface and the rate of fall of the water level in the reservoir was recorded over time intervals until five consecutive consistent readings were achieved, which typically occurred within 60 minutes. The IR was calculated using the Reynolds & Elrick (1990) method.

2.2.6 Penetration resistance and bulk density

An electronic cone penetrometer (Field Scout SC 900, Spectrum Technologies, Inc., Aurora, IL, equipped with 1.27 cm diameter tip) was used to measure PR. The PR measurement was also made near the location of each infiltrometer test.

For determination of soil BD, soil cores were collected from the top 2.5 – 15 cm of the soil profile using a 5-cm diameter core sampler (AMS Inc., American Falls, ID) from each plot at an approximate distance of 50 cm from the infiltration ring. The upper 2.5 cm was discarded to avoid any potential compaction caused by the sampler’s hammer. Samples were oven dried to constant weight at 105 °C and weighed.

2.2.7 Root mass density

Soil cores were taken after the infiltration test with a root core sampler (7.3-cm diameter and 60-cm height) equipped with a sliding hammer. The sampling depth was 30 cm. The intact root cores were cut into three depth ranges (0 – 7.5, 7.5 – 15, and 15 – 30 cm) and each sample was washed separately in a 2-mm sieve (A.S.T.M.E.-11 specification, Fisher Scientific Company, Chicago, IL) with tap water. Roots retained on the sieve were oven dried at 65°C for 48 h and then weighed for root mass density and root distribution estimates. The root mass density was calculated for each depth by dividing dry root mass (kg) by the soil core volume (m^3). Root distribution was calculated by dividing root mass at each depth interval by the total root mass for the whole sample.

2.2.8 Statistical analysis

Statistical analyses were carried out using SAS 9.4 (SAS, Cary, NC). Normality tests were conducted for all data using the Shapiro-Wilks test, and IR data were log-transformed to achieve normal distributions and was back transformed to orriginal scale for reporting the data. within each site, the IR, BD, and RMD data were analyzed using PROC GLIMMIX as repeated measures with treatments (cover and compost) and time (five sampling times) as fixed factors and their replications as a random factor. Different covariance structures [1st order autoregressive (AR (1)), compound symmetry (CS), and unstructured (UN)], were fitted to all data. Akaike’s information criterion (AIC) was used to assess covariance structures. The covariance structure having the smallest Akaike’s information criterion was selected which is compound symmetry .

In addition, infiltration data from all sites were combined to estimate the effects of treatments over a variety of regions (Coastal Plain, Piedmont, and Mountains), where the effects of treatments and regions were considered as fixed effects and their replications as random effects. Comparisons between means were made using the Bonferroni test (Maxwell, 1980) when the F-value in the ANOVA was statistically significant ($P < 0.05$).

2.3 Results and Discussions

2.3.1 Penetration resistance and bulk density

The PR values varied with time of sampling as a result of soil moisture content and increased with depth (data not shown), as has been reported previously (Ayers and Perumpral, 1982). After 24 months of establishment for CP, PD, and MT, the average PR values remained below the critical value (2 Mpa) for root penetration, as suggested by Martino & Shaykewich (1994), within the tillage depth (15 cm) and somewhat beyond the tillage depth (Fig. 2.1).

The analyses of variance for the BD across sites (combined) and within sites are summarized in Tables 2.5 and 2.6, respectively. There were consistent differences in bulk density as a result of compost incorporation across sites (Fig 2.2). Vegetation type did not affect the BD values at any site. Compost incorporation lowered BD by 16, 23, and 20% at CL, PD, and MT, respectively (Table 2.7). For all sites, BD ranged from 0.96 to 1.06 g cm^{-3} for the compost treatments, and from 1.20 to 1.32 g cm^{-3} for treatments without compost. Compost consistently maintained lower BD throughout the experiment period (30 months) as there was no interaction between compost and time at any site (Table 2.6).

At the CP site, the initial (6 months) overall average BD for all plots was surprisingly higher (1.26 g cm^{-3}) than after 12 months (1.03 g cm^{-3}), however, BD increased gradually in the subsequent measurements' intervals. After 30 months the BD was 1.21 g cm^{-3} and was not different ($P \geq 0.05$) from the initial BD (1.26 g cm^{-3}) (Table 2.7. Bulk density over time at each site by treatment.. At the PD site, the overall BD remained relatively constant with no changes during the experiment period, although slightly higher BD was observed after 30 months (1.21 g cm^{-3}) than after 6 months with BD of 1.16 g cm^{-3}) (Table 2.7). At the MT site, the BD remained stable during the first three intervals (6 to 18 months). After 24 months, BD increased to 1.18 g cm^{-3} and was greater ($p \leq 0.05$) than all other BD values through the experiment period. However, BD decreased to 1.10 g cm^{-3} at the next measurement time (30 months).

Our results from each site show that compost incorporation considerably reduced BD compared to tillage alone regardless of soil texture variability among sites. Several studies related to urban soil remediation have found that tillage or/and compost can reduce BD of compacted soils. Our findings were in consistent with those of Olson et al. (2013) who found that compost addition (7-cm depth) was more effective than tillage alone by reducing soil BD in remediated compacted soils . Likewise, Mohammadshirazi et al. (2017) evaluated tillage and amendments impacts on IR and BD in five sites across North Carolina. They found that tillage reduced bulk density in compacted soils, and the effect of tillage was sustained to up to 32 months after tillage. They also tested compost incorporation with tillage at a similar application rate, and found that the compost reduced BD in two sites out of five compared to tillage alone, and particularly in fine-textured soils.

In our study the average BD at each site also did not change after 30 months of establishment time when compared to the 6 month values, indicating that tillage and compost effects on BD can persist for at least 3 years. Logsdon et al. (2017) observed an improved soil quality of post-construction soils when compost was incorporated (5 cm) with either aeration or tillage, resulting in lower surface BD compared to the original conditions with the effect persisting for at least 3 years. However, they recommended a periodic compost incorporation as the compost decomposes over time.

2.3.2 Infiltration

Across all sites, compost and wildflowers increased the IR by 41% and 36%, respectively, compared to without compost and grass treatments (Tables 2.5 and 2.9). The interaction between location x compost showed that compost incorporation improved IR at PD and MT sites, but not at CP (Fig. 2.3). The IR ranged from 44.6 to 88.4 cm h^{-1} with compost, and 22.4 to 47.9 cm h^{-1} without compost incorporation at PD and MT, respectively. At the CP site IR were not found to be different with or without compost, though the relative trend with compost addition was the same as at the other sites (Fig. 2.3).

At the CP and MT sites, the IR was greater by 43 and 30%, respectively, in the wildflower treatment than in the grass treatment (Table 2.8). At PD, there was a 41% difference between wildflowers and grass significant at $P \leq 0.1$. A large amount of variability was observed in IR data for the PD site.

The overall IR remained relatively constant throughout the experiment period at each location with the exception of the 24-month evaluation, when IR decreased ($p \leq 0.05$) at CL and MT (Table 2.9). However, IR returned to prior levels at 30 months in both cases. The reduction in IR at 24 months may be due to the antecedent soil moisture content as a heavy rain occurred before the IR tests, resulting in lower IR values (Fig. 2.4).

Compost addition improved infiltration at PD and MT by 50 and 46%, respectively, but not at CP. Therefore, the compost effect on IR appeared to be site-specific and might be related to the soil texture. At the PD and MT sites with high clay contents of 28.9 and 34.8%, respectively, soils benefited from compost incorporation most likely due to reduced BD and improved soil porosity. While, At the CP site where the texture is much sandier (82.1 %) with low clay content (4.1%), compost incorporation did not improve the soil structural properties for infiltration. These results are in agreement with those of Weindorf et al. (2006), who suggested that infiltration is more affected by soil texture and mineralogy than by compost application. Brown and Cotton (2011) found that compost application improved both water holding capacity and IR in coarse and fine-textured soils. However, they observed largest improvements in water holding capacity in the coarse-textured soils and the largest improvements in infiltration in the fine-textured soils.

Similar to our study, Mohammadshirazi et al. (2017) found improved infiltration with compost addition compared to tillage alone only at two sites out of five . In fact, they found that compost addition did not improve infiltration at their PD and MT sites, which it is somewhat in contrast to our results. However, their IR were relatively similar to ours except for our MT site after 30 months. Also, they evaluated two tillage depths, shallow (15 cm) and deep (30 cm), and they observed an up to threefold increase in IR regardless of the tillage depth compared to compaction treatment. However, they found that both tillage treatments had a similar IR. Deeper tillage was also studied by Chen et al. (2014) who found that compost incorporation down to 60 cm improved soil saturated hydraulic conductivity relative to top soil application and shallow tillage practices. However, deep tillage or subsoiling is not only expensive but impractical in many urban areas where buried utility lines and trees might exist which would make deep tillage difficult (Chaplin et al., 2008). Curtis & Claassen (2009) indicated that tillage alone maybe be sufficient to improve infiltration along roadcut areas if soils have adequate nutrients to support vegetation. Additionally, they found greater plant biomass with incorporated compost compared to tillage alone.

The overall IR was higher under wildflowers than grass cover at all sites, although the difference was less significant at PD. The IR might be affected by the species diversity in the wildflowers mix due to the variety of annuals, perennials, and biennials with different root system types (Table 2.2 and 2.3). Fischer et al. (2015) indicated that plant species richness with different functional groups (grasses, small herbs, tall herbs, and legumes) improved IR, and they explained that this was most likely via changing soil porosity and root mass in the studied area. Selbig and Balster (2010) found that prairie vegetated rain gardens had higher IR than those with grass after five year of establishment. They attributed this to the deeper roots for the prairie species and the greater biological activity of flora and fauna may have resulted in greater pedoturbation and soil development under prairie species relative to grass.

2.3.3 Root density and distribution

Root mass density was affected by time at each site and depth, except the deepest sampling depth (15-30 cm) at CP, where there was no time effect (Table 2.10). Averaged across all treatments, RMD was mainly affected by the time of measurement across all depth intervals and sites except at CP for 15 – 30 cm depth (Table 2.11). Root mass density decreased with depth regardless of the vegetation type or compost level (Fig. 2.5).

At the CP site, neither compost nor vegetation type showed any differences in RMD at any depth. The RMD was lowest (0.72 kg m^{-3}) at 6 months and then increased for subsequent measurements (12, 18, 24, and 30) at the 0 – 7.5 cm depth. At the 7.5 – 15 cm depth, RMD increased over time from 0.55 kg m^{-3} at 6 months to 1.34 kg m^{-3} after 30 months. The RMD remained relatively constant over time at the 15 – 30 cm depth.

At the PD site, RMD was higher under the grass than in the wildflowers at the 0 – 7.5 cm depth, while similar RMDs were observed at deeper depths (7.5 – 15 and 15 – 30 cm). Again, compost did not affect RMD at any depth. There was a significant interaction between vegetation and time particularly for the wildflowers where the RMD was significantly higher at 24 and 30 months than at 6 and 12 months (Fig 2.6).The averaged RMD varied with sampling times, where RMD increased from 1.3 kg m^{-3} (6 months) to 3.33 kg m^{-3} (30 months) at 0 – 7.5 cm depth, and slightly increased after 30 months compared to 6 months RMD for the deeper depths.

At the MT site, compost level and vegetation type did not affect RMD at 0 -7.5 and 7.5 – 15 cm depths, however, RMD was higher under grass compared to wildflowers at 15 – 30 cm depth. The RMD at 30 months was higher ($p \leq 0.05$) than all preceding sampling times across all sites. Similar to PD, an interaction between vegetation and time was identified where the RMD for the wildflowers at 30 months was also higher than all other sampling times (Fig. 2.6).

Overall, grass and wildflowers had a relatively similar RMD across depths. We expected that wildflowers would have more root mass than grass. This was not the case, however, we observed different roots characteristics between grass and wildflowers. These were not quantified. Therefore, more research should be conducted to investigate the effect of different roots characteristics on soil infiltration.

As expected, more than 60 % of the roots were within 0 – 7.5 cm depth regardless of vegetation type or compost level, and amounts decreased to approximately 24.5% and 8% at depths 7.5 – 15 cm and 15 -30 cm, respectively. The effect of tillage on root distribution was evident in the layer affected by tillage. Almost 90% of the roots were found to be within the 15 cm depth, which was the depth of tillage. The concentrated root growth within the tilled layer might be explained by the low BD values (Fig. 2.5) within the top 15 cm, which may have provided a favorable condition for root growth. Because the BD below 15 cm was not measured in this study, we cannot definitively say that the RMD was primarily driven by the BD. However, the increase in the PR from 1 MPa to 2 MPa in the depth range 15 to 30 cm might be related to a higher BD below the tillage depth as the PR depends greatly on the BD (Hernanz et al., 2000) (Fig. 2.1). It is also possible that the compost and fertilizers incorporation enhanced the root growth within the tilled layer due to increased soil fertility relative to deeper layers. Haynes et al. (2013) found that tillage promoted deeper and denser grass roots particulary below 15 cm down to 50 cm through the soil profile compared to core aeration and compaction treatments. Likewise, Mohammadshirazi et al. (2017) reported higher grass root density under shallow (15 cm) and deep (30 cm) tillage treatments relative to compacted soil in two out of three sites. Moreover, when compost was applied, higher root density was achieved at the 15 – 30 cm depth compared to compacted soils (Mohammadshirazi et al., 2017).

2.3.4 Implications and challenges

This study documents potential improvements in soil infiltration with compost amendments and wildflower groundcover. Our results suggest that this approach is a viable practice and could be integrated with stormwater mitigation practices in urban areas with best management practices and low impact developments. The IR values were considerably high and ranged from 40 to 88.4 cm h^{-1} (Table 2.9) under compost and wildflower treatments, which might accommodate high-intensity storms (return period ≥ 10 years) or in low-lying areas that receive stormwater. Therefore, wildflowers strips with soil compost amendments may be a practical management solution for linear transportation systems or highway interchanges to mitigate the effects of highway runoff on receiving waters or on areas that were not designed for stormwater management. Moreover, wildflower planted-areas can be seen as a low-mow maintenance regime as in our study wildflowers were mowed once a year as compared to four times for the grass, which complies with the NCDOT objectives to reduce mowing costs by implementing cost-effective practices. Based on the economic analysis of roadside vegetation management within the NCDOT by Martin & Gaustad (2017), the estimated savings were about

$ 2.5 million when one to two mowing cycles were eliminated by plant growth regulators for grass.

One of the challenges that may arise when utilizing wildflower groundcovers is the differences in seeds price between wildflowers and grass seeds. In this study, the cost (dollar /seeded m^2) of the wildflower mix was double and triple that of the west and east grass mixes, respectively. However, taking into consideration the low maintenance of the wildflowers may reduce or compensate for these cost differences. The longevity of wildflowers stands and invasive weeds are another potential challenge, therefore, appropriate establishment techniques are necessary to maintain the longevity of wildflowers on roadsides.

Another challenge might be the decomposable nature of compost which might limit the long-term beneficial impacts; a periodic application of compost has been recommended (Logsdon et al., 2017). However, according to Olson et al. (2013), if successful vegetation is present and taking advantage of compost, roots might penetrate deep into the soil profile creating macropores that may extend the beneficial impacts provided by the compost. Also, compost appeared to be more effective in fine-textured soils than course- textured soils, therefore, future research should determine how to optimize compost application rates for different soil textures to maximize its effectiveness as a remediation technique for urban soils restoration

2.4 Conclusions

1. Compost application along with tillage significantly reduced soil BD compared to tillage alone across all sites. The effects of tillage and compost on BD were maintained for 30 months after establishment. Neither grass nor wildflowers affected the soil BD.

2. Compost was effective in improving IR for the Piedmont and Mountain sites by about 50 and 46%, respectively, compared to tillage alone, suggesting that the effectiveness of compost on IR is site specific and might relate to soil texture at each site.
3. Wildflowers improved IR by 43, 41, and 30% for the Coastal Plain, Piedmont, and Mountains, respectively, compared to grass. This trend did not appear to relate to root mass density differences between wildflowers and grass. Root densities were similar between cover types and were largest within the tilled layer.
4. This study demonstrated that wildflowers were superior to grass regarding IR and low maintenance requirements and could be a viable alternative vegetative cover in vegetative stormwater practices.
5. Cost of the wildflowers seed, longevity of stand, and invasive weeds may present major challenges when utilizing wildflowers in roadside areas.

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Tables and Figures

Table 2.1. Soil texture and sand, silt, and clay fractions for Coastal Plain, Piedmont, and Mountain sites.

Site	Texture	Sand	Silt	Clay
	--------		--------% --------	
Coastal Plain	Loamy sand	82.1	13.8	4.1
Piedmont	Sandy clay loam	50.2	20.9	28.9
Mountain	Clay loam	42.0	23.1	34.8

Table 2.2. Common and scientific names for Pollinator Wildflower Seed Mix (Southeast region) from American Meadows Inc., Shelburne, Vermont, along with life cycle.

Common Name	Scientific Name	Life Cycle
Butterfly Milkweed	*Asclepias tuberosa*	Perennial
Patridge Pea	*Chamaecrista fasciculata*	Annual
Lance Leaved Coreopsis	*Coreopsis lanceolata*	Perennial
Plains Coreopsis	*Coreopsis tinctoria*	Annual
Cosmos Sensation Mix	*Cosmos bipinnatus*	Annual
Purple Coneflower	*Echinacea purpurea*	Perennial
California Poppy	*Eschscholzia californica*	Annual
Blanket Flower	*Gaillardia aristata*	Perennial
Dwarf Sunspot Sunflower	*Helianthus annuus*	Annual
Meadow Foam	*Limnanthes douglasii*	Annual
Dwarf Lupine Pixie Delight Mix	*Lupinus hartwegii*	Annual
Perennial Lupine	*Lupinus perennis*	Perennial
Arroyo Lupine	*Lupinus succulentus*	Annual
Bee Balm / Wild Bergamont	*Monarda fistulosa*	Perennial
Lacy Phacelia	*Phacelia tanacetifolia*	Annual
Mexican Hat	*Ratibida columnaris*	Perennial
Crimson Clover	*Trifolium incarnatum*	Annual

Table 2.3. Common and scientific names for the Southeast Wildflower Seed Mix from American Meadows Inc., Shelburne, Vermont, along with life cycle.

Common Name	Scientific Name	Life Cycle
Siberian Wallflower	*Cheiranthus allionii*	Perennial
Shasta Daisy	*Chrysanthemum maximum*	Perennial
Lance-Leaf Coreopsis	*Coreopsis lanceolata*	Perennial
Plains Coreopsis	*Coreopsis tinctoria*	Annual
Wild Cosmos	*Cosmos bipinnatus*	Annual
Chinese Forget-Me-Not	*Cynoglossum amabile*	Annual
Sweet William	*Dianthus barbatus*	Biennial
Purple Coneflower	*Echinacea purpurea*	Perennial
California Poppy	*Eschscholzia californica*	Annual
Globe Gilia	*Gilia capitata*	Annual
Indian Blanket	*Gaillardia pulchella*	Annual
Baby's Breath	*Gysophila elegans*	Annual
Rose Mallow	*Lavatera trimestris*	Annual
Blazing Star or Gayfeather	*Liatris spicata*	Perennial
Scarlet Flax	*Linum grandiflorum rubrum*	Annual
Blue Flax	*Linum perenne lewisii*	Perennial
Sweet Alyssum	*Lobularia maritima*	Annual
Wild Lupine	*Lupinus perennis*	Perennial
Texas Bluebonnet	*Lupinus texensis*	Annual
Evening Primrose	*Oenothera lamarckiana*	Biennial
Red Poppy/Shirley Poppy	*Papaver rhoeas*	Annual
Drummond Phlox	*Phlox drummondi*	Annual
Clasping Coneflower	*Rudbeckia amplexicaulis*	Annual
Black-eyed Susan	*Rudbeckia hirta*	Perennial
Gloriosa Daisy	*Rudbeckia gloriosa*	Perennial
Scarlet Sage	*Salvia coccinea*	Perennial

Table 2.4. Grass and wildflowers seeding rates, fertilizer, and lime application rates.

Vegetation	Seeding rate	Fertilizer 10-20-20	Lime
	----------------kg ha^{-1}----------------		
Grass East			
Tall fescue	84.0	560.4	4483.4
Bermudagrass	28.0		
Grass West			
Tall fescue	112.1	560.4	4483.4
Kentucky bluegrass	16.8		
Hard fescue	33.6		
Rye grain	28.0		
Wildflowers			
Pollinator Wildflower Mix	48.8	560.4	4483.4
Southeast Wildflower Mix	48.8		
Crimson clover	11.1		

Table 2.5. Combined analysis ANOVA for bulk density and infiltration rate.

Effect	Bulk density	Infiltration
Cover	NS	**
Compost	***	***
Cover x compost	NS	NS
Location	***	**
Cover x location	NS	NS
Compost x location	*	†
Cover x compost x location	NS	NS

†, *****, ******, and *** indicate significant p-values for α= 0.1, = 0.05, = 0.01 and = 0.001, respectively.

Table 2.6. Summary of the statistical analysis for bulk density for the main effects and interactions within locations.

Effect	Coastal Plain	Piedmont	Mountain
Vegetation	NS	*	NS
Compost	***	***	***
Vegetation*compost	NS	*	NS
Time	***	*	***
Vegetation*time	NS	NS	NS
Compost*time	NS	NS	NS
Vegetation*compost*time	NS	NS	NS

*, and *** indicate significant p-values for α = 0.05 and = 0.001, respectively.

Table 2.7. Bulk density over time at each site by treatment.

Treatment	Levels	Coastal Plain	Piedmont	Mountain
			Bulk density, g cm^{-3}	
Compost	with	1.05b	1.01b	0.96b
	without	1.26a	1.33a	1.20a
			Bulk density, g cm^{-3}	
Vegetation	Grass	1.17a	1.15a	1.09a
	Wildflowers	1.14a	1.18a	1.07a
Time	Months		Bulk density, g cm^{-3}	
	6	1.26a	1.16a	1.00bc
	12	1.03c	1.16a	1.06bc
	18	1.10bc	1.13a	1.07bc
	24	1.17ab	1.18a	1.18a
	30	1.21ab	1.21a	1.10b

Within each treatment level per site means followed by the same letter within a column are not different (p = 0.05).

Table 2.8. Summary of the statistical analysis for infiltration (IR) for the main effects and interactions.

Effect	Coastal Plain	Piedmont	Mountain
Vegetation	*	†	*
Compost	NS	***	*
Vegetation*compost	NS	NS	NS
Time	**	NS	***
Vegetation*time	NS	NS	NS
Compost*time	NS	NS	NS
Vegetation*compost*time	NS	NS	NS

†, *****, ******, and *** indicate significant p-values for α= 0.1, = 0.05, = 0.01 and = 0.001, respectively.

Table 2.9. Infiltration rates (IR) over time measured at each site by treatment.

Treatment	Levels	Coastal Plain	Piedmont	Mountain
			Infiltration rate, cm h^{-1}	
Compost	with	40.0a	44.6a	88.4a
	without	33.1a	22.4b	47.9b
			Infiltration rate, cm h^{-1}	
Vegetation	Grass	26.5b	24.9.8b	56.3b
	Wildflowers	46.6a	42.3a	80.0a
Time	Months		Infiltration rate, cm h^{-1}	
	6	42.6a	35.6a	84.8a
	12	46.2a	40.8a	60.9a
	18	40.9a	40.2a	53.7ab
	24	18.8b	21.3a	22.3b
	30	34.2ab	21.3a	119.3a

Within each treatment level per site means followed by the same letter within a column are not different (p = 0.05).

Table 2.10. Summary of the statistical analysis for root mass density (RMD) for the main effects and interactions

Depth/Effect	Coastal Plain	Piedmont	Mountain
0 – 7.5 cm			
Vegetation	NS	*	NS
Compost	NS	NS	NS
Vegetation*compost	NS	NS	NS
Time	***	**	***
Vegetation*time	NS	*	NS
Compost*time	NS	NS	NS
Vegetation*compost*time	NS	NS	NS
7.5 – 15 cm			
Vegetation	NS	NS	NS
Compost	NS	NS	NS
Vegetation*compost	NS	NS	NS
Time	***	*	***
Vegetation*time	NS	NS	**
Compost*time	NS	NS	NS
Vegetation*compost*time	NS	NS	NS
15 – 30 cm			
Vegetation	NS	NS	NS
Compost	NS	NS	NS
Vegetation*compost	NS	NS	NS
Time	NS	**	***
Vegetation*time	NS	NS	NS
Compost*time	NS	NS	NS
Vegetation*compost*time	NS	NS	NS

*, **, and *** indicate significant p-values for α= 0.05, = 0.01 and = 0.001, respectively**.**

Table 2.11. Root mass density and distribution at each depth and time.

Site/effect		Root mass density, kg m^{-3}		
		Depth, cm		
Coastal Plain		0 – 7.5	7.5 - 15	15 - 30
Time	Months			
	6	0.72b	0.55b	0.18a
	12	2.30a	0.87ab	0.21a
	18	2.56a	1.56a	0.42a
	24	2.47a	0.96ab	0.34a
	30	2.87a	1.34a	0.24a
Piedmont				
Vegetation	Grass	2.20a	0.53a	0.23a
	Wildflowers	1.23b	0.66a	0.20a
Time	Months			
	6	1.30b	0.80ab	0.26ab
	12	0.97b	0.23b	0.11b
	18	1.70ab	0.48ab	0.18ab
	24	1.70ab	0.61ab	0.18b
	30	3.33a	0.91a	0.32a
Mountain				
Vegetation	Grass	2.30a	0.55a	0.25a
	Wildflowers	2.00a	0.70a	0.20b
Time	Months			
	6	1.16b	0.56b	0.21b
	12	1.83b	0.43b	0.12b
	18	1.30b	0.39b	0.17b
	24	1.66b	0.42b	0.20b
	30	4.81a	1.37a	0.44a

Within each treatment level per site means followed by the same letter within a column are not different ($p = 0.05$).

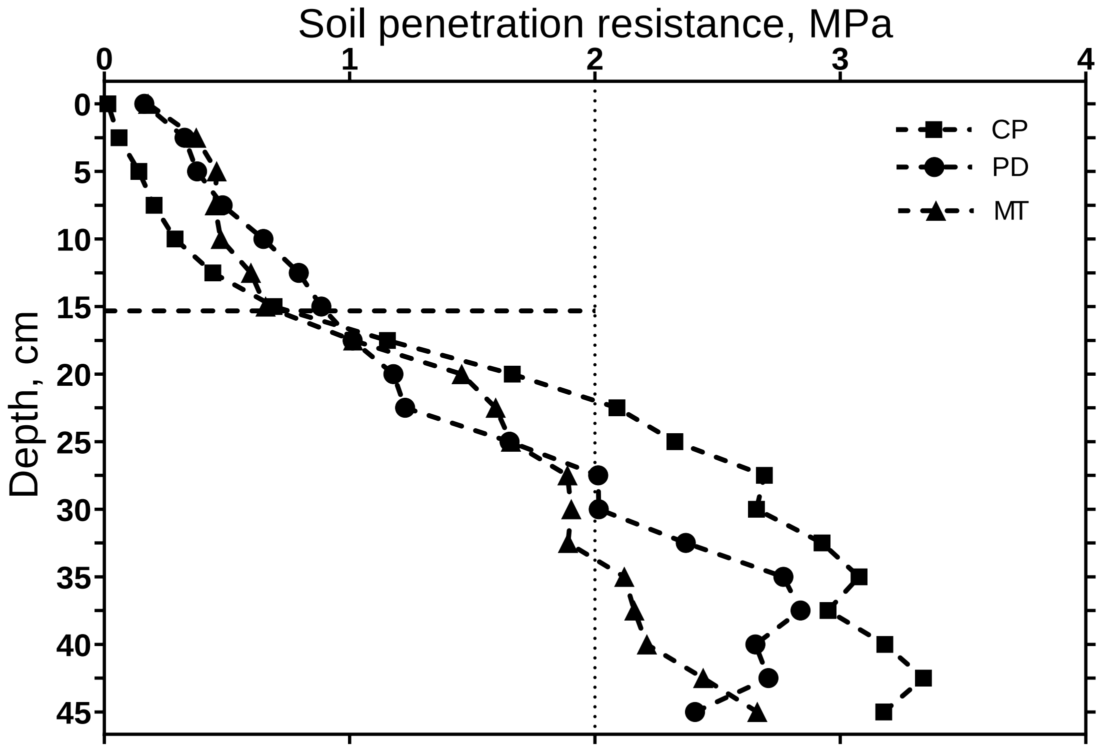

Figure 2.1. Averaged soil penetration resistance versus depth at Coastal plain (CP), Piedmont (PD), and Mountain (MT) sites after 24 months. Vertical dotted line represents the critical value for root penetration. Horizontal dashed line represents tillage depth.

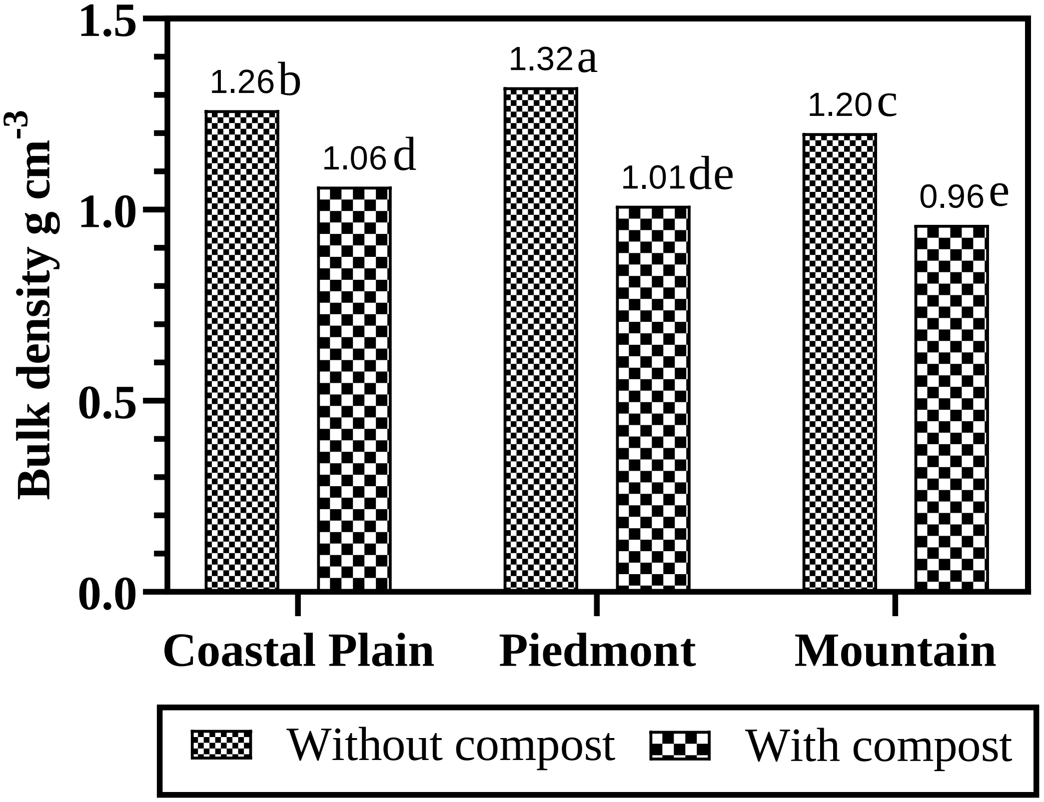

Figure 2.2. Bulk density data collected across locations and years for location x compost interaction effect at Coastal Plain, Piedmont, and Mountain sites. Values with the same letter within each depth are not different (p = 0.05).

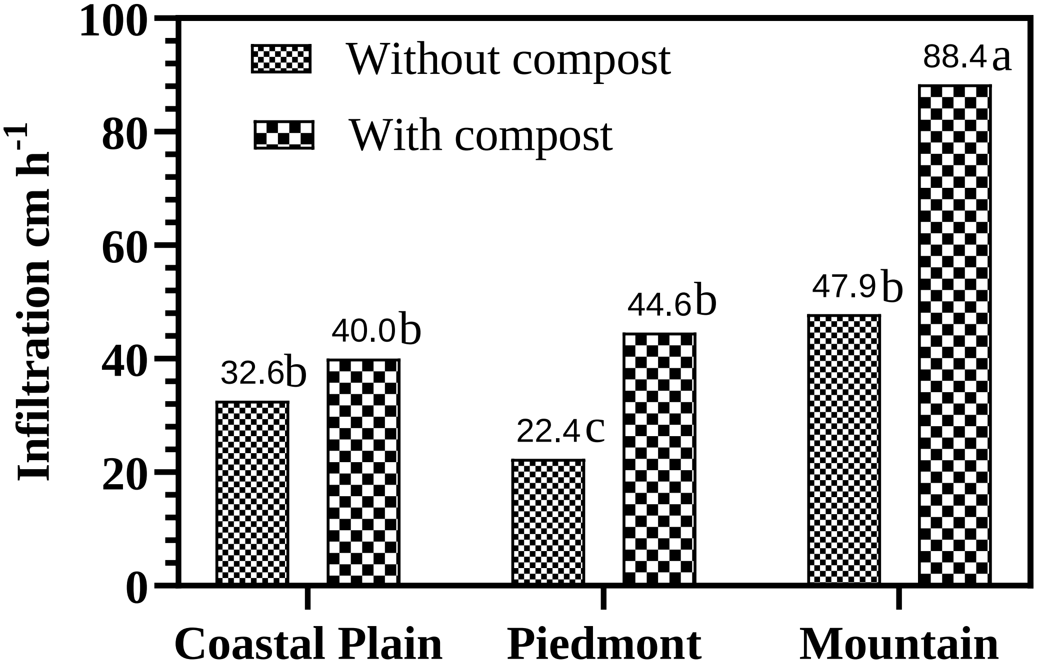

Figure 2.3. Infiltration rate data collected across locations and years for location x compost interaction effect at Coastal Plain, Piedmont, and Mountain sites. Values with the same letter within each depth are not different (p = 0.05).

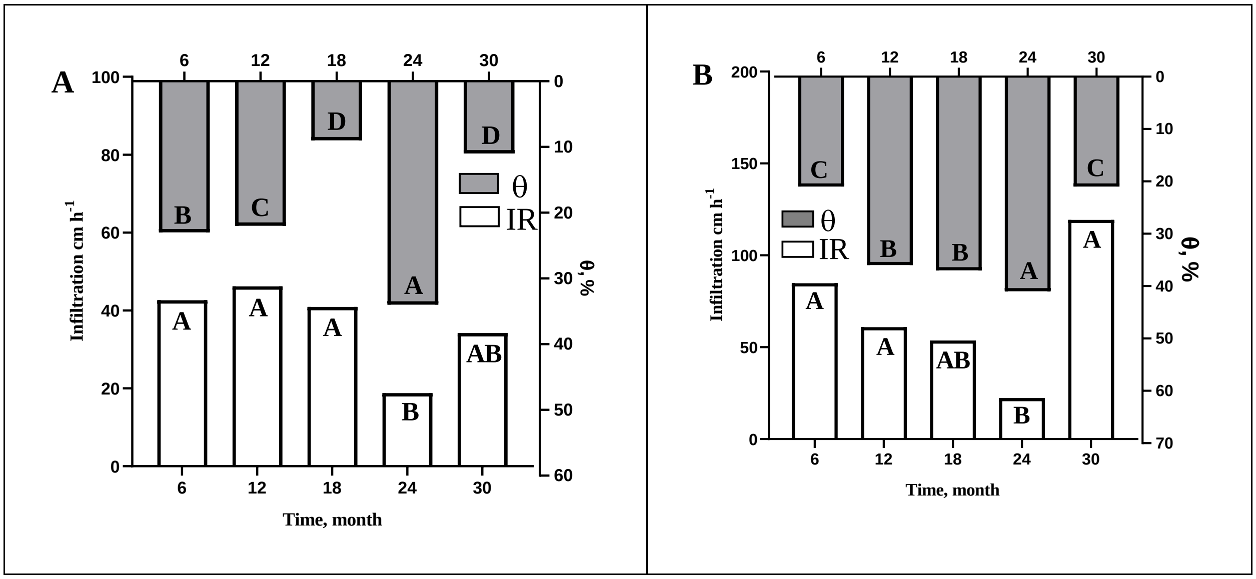

Figure 2.4. Variability in the infiltration rate (IR) and soil moisture content (θ) over time at (A) Coastal Plain and (A) Mountain sites. Same letters for IR and θ separately are not different ($p = 0.05$).

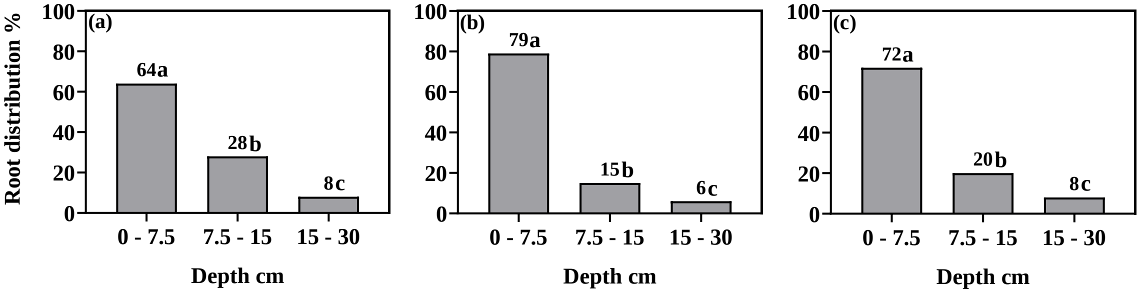

Figure 2.5. Root distribution with depth for grass and wildflowers combined at (a) Coastal Plain, (b) Piedmont, and (c) Mountain sites. Values with the same letter within each depth are not different ($p = 0.05$).

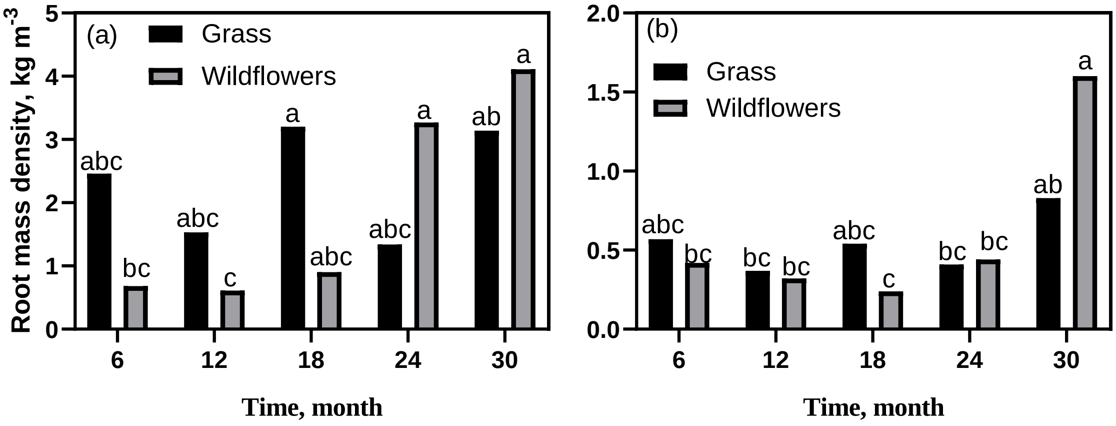

Figure 2.6. Interaction between vegetation roots and time for (a) Piedmont site at depth (0 – 7.5 cm), and (b) Mountain site at depth (7.5 – 15cm). Same letters are not different ($p = 0.05$).

Chapter 3: Compost Application and Vegetation Management for Traffic Compaction Alleviation

Abstract

Wheel traffic can lead to soil compaction and degradation of soil physical properties in mowed areas. We are currently investigating the effects of vegetation type (grass, wildflowers) and compost on soil physical properties after tillage to alleviate compaction. The aim of this study was to investigate the effect mower tractor traffic on these soil properties within each of these treatment combinations. Penetration resistance (PR), bulk density (BD), and infiltration rate (IR) were measured twice per year during the 2016 - 2019 growing seasons. Wildflowers or grass were seeded on tilled soil (15 cm) with or without incorporated compost in plots located in the Coastal Plain (CP), Piedmont (PD), and the Mountain (MT) regions of North Carolina. Grass was mowed 4 times per year between May and November while wildflowers were mowed once at the end of the growing season, with mower wheels maintained in the same location within the plots. Over a 30 month period, PR, BD, and IR were measured under the wheel traffic and between wheels at the beginning and the end of each growing season. Traffic resulted in increases in PR and BD, and decreased IR by 68 to 91% across all locations/treatments. Infiltration rate was less afftected by traffic under wildflowers compared to grass. Compost addition generally reduced the effects of traffic. This study suggests that areas planted to wildflowers are likely to have less wheel traffic compaction impacts than grassed areas, and incorporating compost may further reduce impacts.

3.1 Introduction

Soil compaction may be the most detrimental effect of vehicle traffic. Frequent traffic of machinery and equipment causes a breakdown of soil structure in the topsoil layer and considerable compaction in the lower layers (Chan et al., 2006; Reintam et al., 2009; Chamen et al., 2015). The infiltration rate is an essential parameter of soil, which is influenced by agricultural traffic and its intensity. Therefore, the IR of the soil is a good indicator of the soil compaction (Halvorson et al., 2003). In compacted soils the IR of rainwater decreases and the risk of surface runoff increases (Li et al., 2001), which lead to erosion due to low aggregate stability and reduced soil pores. Li et al. (2001) found that the non–compacted soil had 4 or 5 times higher IR than compacted soil.

Traffic compaction results in an increase in soil BD values which negatively affect the soil IR in comparison to the non–trafficked soil (Botta et al., 2006). The BD is also one of the key indicators of the soil compaction (Hamza & Anderson, 2005). As soil compaction occurs, the BD increases due to constant mass and reduced volume (Halvorson et al., 2003). Soil compaction naturally varies with soil type; sandy soils have naturally higher BD than clay soils due to the many small pores associated with clays. Bulk density values of clay, clay loam, and silt loam soils normally range from 1.00 to 1.60 while sand and sandy loam soils normally range from 1.20 to 1.80 g cm^{-3} (Brady, 1974). Compacted soils may have BD values of near 2.00 g cm^{-3} if severely trafficked (Raper, 2005).

Soil compaction can also be evaluated using a penetrometer where soil PR are evaluated. The PR measurement has advantages over BD as data from a whole soil profile can be simply obtained but limited by the penetrometer length (Raper, 2005). On the other hand, the PR measurement has also some disadvantages, the main one is its soil moisture dependence (Nawas, 2016). Also, variation in soil texture and other physical properties among locations or soil horizons may complicate PR interpretation as an indicator of soil compaction (Mulqueen et al., 1977).

Management strategies such as conservation tillage, reduced tillage and soil organic matter application have been suggested to avoid the detrimental effects of intensive tillage and traffic (Raper, 2005; Batey, 2009). Organic matter is generally assumed to reinforce the soil to reduce compaction (Mujdeci et al., 2017), and to decrease its sensitivity to mechanical damage even when severe mechanical disruption occurs (Arvidsson, 1998).

Therefore, the aim of this study was to investigate the effects of both mower traffic soil compaction and compost addition on PR, BD, and IR under two vegetation typess with different mowing frequencies (tractor traffic) for a period up to 30 months in three different geographic regions across North Carolina, USA.

3.2 Materials and Methods

Field plots were constructed at three sites across North Carolina representing Coastal Plain (CP), Piedmont (PD), and Mountain (MT) geographic regions of North Carolina. These were located at the Central Crops Research Station (Clayton), Lake Wheeler Road Field Laboratory (Raleigh), and Mountain Horticulture Crops (Mills River) research stations, respectively. The field experiment was initiated in October 2016, one year prior to sampling. Experimental treatments consisted of two vegetation types (grass and wildflowers), two compost levels (with and without), and two tractor traffic treatments (with traffic and without traffic) across all sites. The result was four mainplot treatments: (1) grass without compost (G), (2) grass with compost (GC), (3) wildflowers without compost (W), and (4) wildflowers with compost (WC), and two traffic treatments as subplots in a split plot design. Treatments were replicated four times in a randomized block design. Details on the site characteristics and plots establishment can be found in chapter two.

Grass plots were mowed to 15 cm 4 times a year between May and November , and wildflower plots were mowed once a year in late November after senescence. A rotary cutter tractor (Table 3.1) (Bush Hog) was used in a controlled mowing pattern where two wheels went down the middle of the plots and the other wheels between the plots. Infiltration (IR), bulk density (BD), and penetration resistance (PR) were measured every six months for a period of 18 months in the traffic and no traffic plots. The measurements started 12 months after plots establishment in Fall 2017. One measurement was taken per plot for each parameter at the sampling time. Measurements were conducted in May (Spring) and November (Fall) and repeated periodically for 2017, 2018, and 2019, representing spring and fall growing seasons.

3.2.1 Infiltration rate measurement

Constant head infiltration measurements were taken by using a single ring infiltrometer consisting of a reservoir 150 cm high, with inner diameter of 10 cm connected to a metal ring with 11 cm diameter. The ring was gently driven into the ground to depth of 7.5 cm. A thin layer of gravel was placed on the soil surface to minimize altering the soil surface at the beginning of the infiltration process. A pressure head of 5 cm was established at the soil surface and the rate of fall of the water level in the reservoir was recorded over time intervals until five constant consecutive readings were achieved, which typically occurred within 60 minutes. The IR was calculated using the Reynolds & Elrick (1990) method. The infiltration was measured immediately after traffic, then before traffic in spring 2018, fall 2018, and spring 2019. Also, no mowing occurred between fall and spring measurements in both years.

3.2.2 Bulk density and penetration resistance

For determination of soil BD, soil cores were collected from the top 15 cm soil profile using a 5 cm diameter core sampler (AMS Inc., American Falls, ID) from each plot at an approximate distance of 50 cm from the infiltration ring. The upper 2.5 cm was discarded to avoid any potential compaction caused by the sampler's hammer. Samples were oven dried to constant weight at 105 °C and weighed.

An electronic cone penetrometer (Field Scout SC 900, Spectrum Technologies, Inc., Aurora, IL, equipped with 1.27 cm diameter tip) was used to measure PR. The PR measurement was also made near the location of each infiltrometer test.

3.2.3 Statistical analysis

Statistical analysis for the split-plot design was conducted using the PROC GLIMMIX procedure in SAS version 9.4 (SAS; Cary, NC, USA). Normality tests were conducted for all data using the Shapiro-Wilks test, and IR data were log-transformed to achieve normal distributions. Combined analysis across locations and years were performed for IR and BD as a split-plot design with vegetation, compost, and traffic treatments as fixed factors, and location, year, and their replications as random factors. Penetration resistance (PR) data were combined across time and analyzed for each site individually to remove the effects of soil moisture content from PR readings at sampling times without the need of calibrations for different soil types . Within each site, grass and wildflowers were analyzed separately to evaluate traffic impacts on IR within each vegetation because grass and wildflowers had different traffic intensities. The analysis were performed as a split split-plot design with compost treatments (with and without) as the main plot, traffic (traffic and no traffic)) as sub-plot, and time (four times) as sub sub-plot.

3.3 Results and Discussion

3.3.1 Statistical analysis

The analysis of variance (ANOVA) of BD and IR for the combined experiments revealed a number of significant fixed effects and interactions (Table 3.2) The data with significant interactions were subjected to mean separation test. For the BD, mean separation tests were conducted on the vegetation x compost and vegetation x traffic interaction effects. For the IR, mean separation testing was conducted on the vegetation x compost x traffic interaction effect. Within location IR analysis for grass and wildflowers are shown in Tables 3.3 and 3.4, respectively. For BD and IR, mean separation testing was conducted on the traffic x time interaction effect.

3.3.2 Penetration resistance

Penetration resistance had a tendency to increase with depth regardless of vegetation and traffic treatments, likely as a result of changes in soil texture, gravel content, and structure with depth (Becerra et al., 2010). Tractor traffic increased PR when high traffic in the grass plots, while traffic did not generally increase PR with the low T in the wildflower plots at any site.

Coastal Plain

At the CP site, traffic consistently increased PR in the tilled-only grass plots to a depth of 25 cm (Fig. 3.1). The PR exceeded 2 Mpa at 10 cm and reached 3 Mpa at 15 cm, while the PR remained below 2 Mpa within the tilled layer (15 cm) in non-trafficked areas (Fig. 3.1). Soils compacted to more than 2 MPa have been shown to restrict root growth to varying degrees (Becerra et al., 2010). Compost incorporation generally reduced PR in the traffic area, but this was only significant at 110cm. Traffic did not affect the PR for the wildflowers at any depth (0 - 45 cm) (Fig. 3.2).

Piedmont

At the PD site, traffic increased PR in the tilled layer to 2.1 Mpa at 5 cm depth and 3.0 MPa at 10 and 15 cm depths in the grass treatment and was greater than the no traffic treatment (Fig. 3.3). Similar to CP results, the incorporation of compost did not mitigate the effects of traffic except at the 15 cm depth, but PR values were generally lower than the trafficked soil without compost. Like the CP location, the single annual mowing in the wildflowers did not increase the PR at any depth (Fig. 3.4).

Mountain

The results at the MT site were similar to PD, with traffic significantly increasing PR in the grass plots, regardless of compost incorporation as most depths (Fig. 3.5). There was less separation between the trafficked PR values in plots with and without compost incorporation. In the wildflower plots, there was one significant difference in PR at the 15 cm depth between the trafficked, non-compost plots, and the untrafficked area of the compost plots (Fig. 3.6). Otherwise, there were no differences in PR with or without traffic in the wildflower plots, similar to the CP and PD results.

Mower traffic in the grass plots usually increased PR but did not in the wildflower plots. This difference may be attributed to the mowing frequency (4 vs. 1 per year) or the vegetation, or some combination. The incorporation of compost did not protect the soil from traffic compaction. Botta et al. (2006) reported that high traffic frequency (10 and 12 tractor passes in the same tracks of a light tractor (3.1 Mg)) produced significant increases in PR and dry BD in the entire soil profile to 60 cm depth. Penetration resistance increased under intensive traffic in all sites particularly in the grass plots within the tilled layer (15-cm) and somewhat down to 20 cm at the CP and MT sites. At all sites, PR exceeded 2 Mpa between 5 and 10 cm, which might restrict root growth and penetration, as suggested by Martino & Shaykewich (1994). On the other hand, PR for the wildflowers remained below 2 Mpa within the tillage layer and was not affected by traffic.

3.3.3 Bulk density

Across all locations, compaction by mower traffic caused considerable changes to the BD and were 1.27 and 1.14 g cm^{-3} for traffic and no traffic treatments, respectively. The interaction between vegetation x traffic showed that traffic increased BD in wildflowers and grass treatments, although, the BD was lower in wildflowers across all locations. Traffic increased BD by 12.8 % and 3.3% in grass and wildflowers, respectively. Grass and wildflowers had similar BD under no traffic (Fig. 3.7A). Mower traffic increased BD regardless of compost application. However, compost reduced the traffic impact on BD when applied, and was 1.15 g cm^{-3} in the compost amended plots compared to 1.40 g cm^{-3} for without compost plots (Fig. 3.7B). Furthermore, traffic increased BD in the grass regardless of compost application (Fig. 3.8A). Traffic increased BD in the wildflower plots when no compost was added relative to the plots with compost, but traffic did not increase BD where compost had been incorporated (Fig. 3.8B).

Results showed that mower traffic substantially increased the BD in the grass plots. Higher BD was expected for the grass plots as a result of four mowing cycles per year compared to wildflowers with one mowing cycle per year. But it appeared that the initial traffic was enough to increase the BD in the wildflower plots without compost. Similar observations were reported by Botta et al. (2008), who reported a significant increase in BD down to 15 cm after one tractor pass. Bakker & Davis (1995) who found that an initial pass of a tractor compacted the topsoil layer. Also, Botta et al. (2008) reported a significant increase in BD down to 15 cm after one tractor pass. In fact, traffic did not increase BD from fall 2017 to spring 2019 in most of the cases. Our observations are in agreement with previous results reported by Botta et al. (2006) who found that BD tended to be less responsive to the number of the tractor passes compared to the PR.

Compost incorporation reduced the negative effects of traffic on both the PR and BD. Despite the increase in BD in the grass plots under traffic, BD remained lower than the without compost plots. Also, compost appeared to be effective when low traffic intensity applied as in the case of wildflowers. These results are similar to those reported by Mujdeci et al. (2017) who found lower BD when compost (35 t ha^{-1}) was mixed into the soil (10-cm) compared to tillage alone after one and three tractor passes. Also, they found that the effect of the traffic was more negative in 0 -10 cm depth as the number of passes increase.

3.3.4 Infiltration

Across all locations, traffic drastically decreased IR in grass and wildflowers regardless of compost incorporation. However, greater IR values were recorded for wildflowers compared to grass in the traffic zone (Fig. 3.9). For the grass, the relative reduction in IR caused by traffic were 86.3% and 83.7 in plots not amended and amended with compost, respectively. While wildflowers were less affected by traffic, and IR decreased by 69.0% and 58.1% for the without compost and compost amended plots, respectively.

Coastal Plain

At the CP site, traffic reduced IR by 74 and 90% for grass and wildflowers, respectively (Fig. 3.10). However, the IR for wildflowers was higher than grass, either with or without traffic. Compost had no effect on IR treatments irrespective of vegetation and tractor traffic. For the grass plots, the traffic zone always had lower IR than the other areas of the plots (Fig. 3.11A). Infiltration increased by 72% and 78% in the no-mowing periods (6 months) between fall 2017 and spring 18, and between fall 2018 and spring 2019, respectively, and decreased by almost 91% between spring 18 and fall 2018 when four mowings occurred in this period (Fig. 3.11A). Immediately after the first mowing (Fall 2017), IR decreased by 78% in the wildflowers. However, IR slightly recovered and was not different from non-traffic areas six months after mowing (Spring 2018), but decreased from 22.9 cm h^{-1} to 4.5 cm h^{-1} as a result of the second mowing in fall (Fig. 3.11A)

Piedmont

At the PD site, the IR response to traffic compaction was similar to the CP site. Tractor traffic significantly reduced IR regardless of vegetation and compost incorporation. The IR in traffic areas in wildflowers was higher than grass by approximately 87% and 76% for with and without compost treatments, respectively, suggesting the detrimental effect multiple mowings on IR in the wheel track (Fig. 3.12). In fall 2017, mowing traffic reduced IR from 67.1 to 2.5 cm h^{-1} and from 14.4 to 0.5 cm h^{-1} in the grass and wildflowers, respectively (Fig. 3.13A-B). Surprisingly, IR was only recovered in the wildflowers after six months (Spring 2018) and was relatively similar to the corresponding IR in the non-trafficked areas, and was maintained until after 12 months (Fall 2018). We did not observe a recovery in IR after the second mowing occurred in the wildflower plots in Fall 18, and IR decreased from 20 to 4 cm h^{-1} in spring 2019 (Fig. 3.13B).

Mountain

At the MT site, wheel traffic markedly decreased IR by 84, 88, 52% in grass, grass+compost, and wildflowers treatments, respectively, while IR for the wildflowers+compost was less affected by traffic (Fig. 3.14). The negative impact of traffic on IR was less drastic in the wildflower plots compared to the grass plots, and IR was always higher. Similar to CP and

PD sites, the first year of mowing substantially decreased the IR in both grass and wildflowers (Fig 3.15A-B). After six months (Spring 2018) without traffic, IR increased from < 1 cm h^{-1} to 3.4 and 7.6 cm h^{-1} for grass and wildflowers, respectively (Fig 3.15A-B).

Different form CP and PD sites, IR increased in spring 2019 despite the traffic (four times for grass and one time for wildflowers) that occurred prior to measurement.

Our results from the three sites showed that the soil compaction induced by traffic drastically decreased IR, and the amount of reduction in IR was substantially related to the intensity of the traffic. Across all sites, the IR under traffic for the grass was seventimes lower than IR under traffic treatment, while two times lower IR in no traffic compared to traffic for the wildflowers. These results indicate the detrimental impacts of mower traffic on IR and that the severity of the damage increases with repeated mowing. The lower IR due to increasing tractor passes agrees with those reported by of Li et al. (2001), who reported that wheel traffic had a large and significant effect on the IR of heavy clay soil, reducing the IR by 4-5 fold. Alamooti & Navabzadeh, (2009), also reported a reduced IR after two and three tractor passes.

Compost incorporation was effective in reducing the negative effects of the traffic on IR in two sites with fine-textured soils. However, this was only evident when light traffic was applied as in the case of the wildflowers. Under traffic, the IR was two to three times higher in the wildflowers+compost compared to wildflowers at any site. This can be explained by the BD in the trafficked wildflowers plots, which ranged from 1.23 to 1.45 g cm^{-3} in without compost plots compared to approximately 1.0 g cm^{-3} in plots amended with across all sites.

The mowing cycles for both grass and wildflowers simulated the roadside vegetation management in North Carolina. On average, the number of mowing cycles across all road types is between 4 and 5 times per year in North Carolina (Martin & Gaustad, 2017). The traffic treatments in this study were applied to the same area (controlled traffic) over time, while roadside grass mowing is most likely to be random and thereby spreading traffic impacts over a larger area. A study on soil compaction related to field traffic during corn harvest revealed that 63% of the field area was exposed to traffic during a single harvest (Duttmann et al., 2014). After the one annual mowing in the wildflower plots, the IR recovered after 6 and 12 months, suggesting that random mowing traffic may have less impact in these areas.

The NCDOT has adopted the Integrated Roadside Vegetation Management approach aiming to encourage stable, self-sustaining vegetation with limited use of mowing and herbicides to reduce the annual maintenance cost for interstate and primary routes (NCDOT, 2019). Therefore, wildflowers, in addition to the IR improvement, might be considered as a cost-effective and efficient approach since wildflowers required less maintenance compared to grass.

3.4 Conclusion

This study evaluated the well-known impacts of field traffic on soil properties and found the severity of the problem may be partially alleviated by adding compost to the soil and/or by adopting vegetation which requires less annual mowing. Traffic increased PR, BD, and decreased IR, and the magnitude of damage was related to the traffic intensity. Traffic increased the PR in the grass plots and was mostly evident in the tilled layer. Traffic did not affect PR in the wildflowers, possibly due to the single annual mowing.

The BD increased with traffic in the grass and wildflowers plots, and the effect was greater in grass. Tractor traffic had a large and significant effect on IR, up to 17 times lower in grass and up to 3.5 lower in wildflowers. The IR had at least partially recovered after 6 and 12 months in the wildflowers when mowing did not occur between the measurements. Compost incorporation appeared to mitigate the negative impacts of traffic in the annually mowed wildflowers but not in the frequently mowed grass

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Tables and Figures

Table 3.1. Tractors Models, weight, and engin power.

Site	Tractor[†]	Wight	Engine power
	Model	kg	KW
Coastal Plain	Massey Ferguson 4609M	3289	67.0
Piedmont	Ford 5000	2660	51.5
Mountain	5205 John Deere	1848	35.8

[†] All tractors specifications were obtained from TractorData LLC, Prior Lake, MN 55372. (https://www.tractordata.com/).

Table 3.2. Combined analysis ANOVA for bulk density and Infiltration rate.

Source of Variation	Bulk density	Infiltration
Compost	**	***
Vegetation	***	***
Vegetation x compost	*	*
Traffic	*	***
Vegetation x traffic	***	***
Compost x traffic	NS	NS
Vegetation x compost x traffic	NS	*

***, **,** and *** indicate significant *p*-values for α= 0.05, = 0.01 and = 0.001, respectively.

Table 3.3. Grass summary of the ANOVA for Infiltration (IR) for the main effects and interactions.

Source of Variation	Coastal Plain	Piedmont	Mountain
Compost	NS	*	NS
Traffic	***	***	***
Compost*traffic	NS	*	NS
Time	***	NS	***
compost *time	NS	NS	NS
Traffic *time	*	NS	***
compost*traffic*time	NS	NS	NS

***,** and *** indicate significant *p*-values for α= 0.05 and = 0.001, respectively.

Table 3.4 Wildflowers summary of the ANOVA for Infiltration (IR) for the main effects and interactions.

Source of Variation	Coastal Plain	Piedmont	Mountain
Compost	NS	**	***
Traffic	***	***	***
Compost*traffic	NS	NS	NS
Time	*	***	***
compost *time	NS	NS	NS
Traffic *time	*	*	***
compost*traffic*time	NS	NS	NS

***, **,** and *** indicate significant *p*-values for α= 0.05, = 0.01 and = 0.001, respectively.

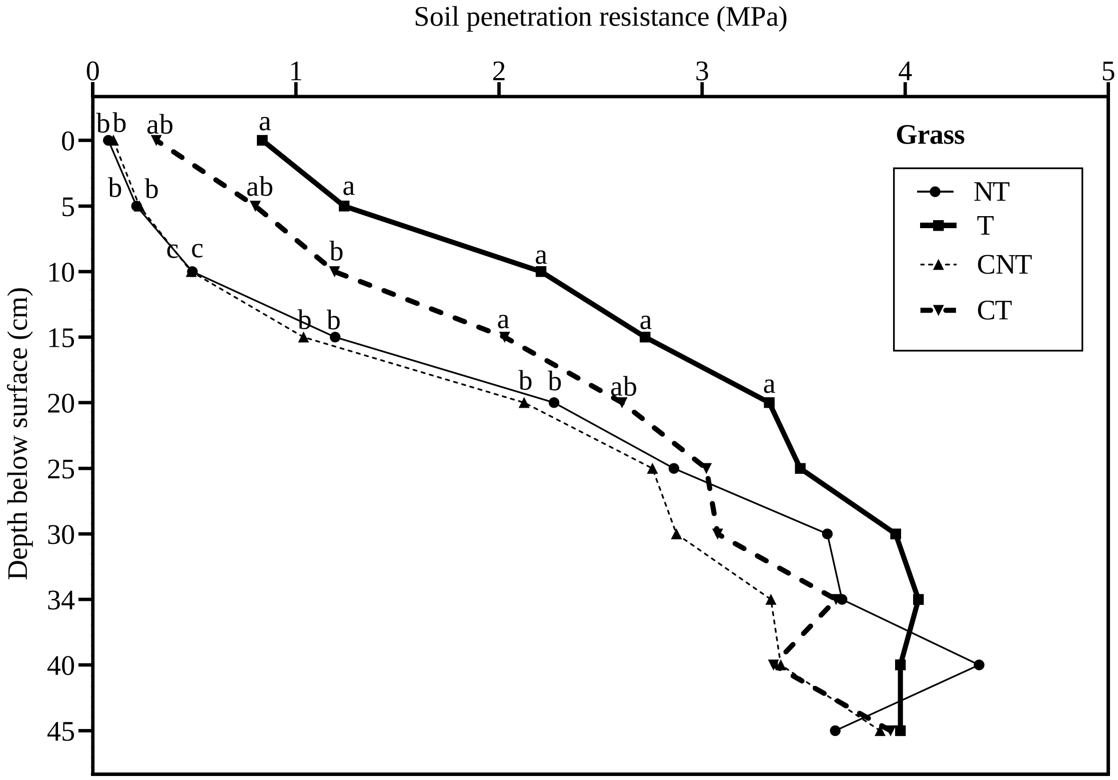

Figure 3.1. Soil penetration resistance versus depth at the Coastal Plain site for grass with no-traffic (NT), traffic (T), compost + no traffic (CNT), and compost + traffic (CT). Values with the same letter within each depth are not different (p=0.05).

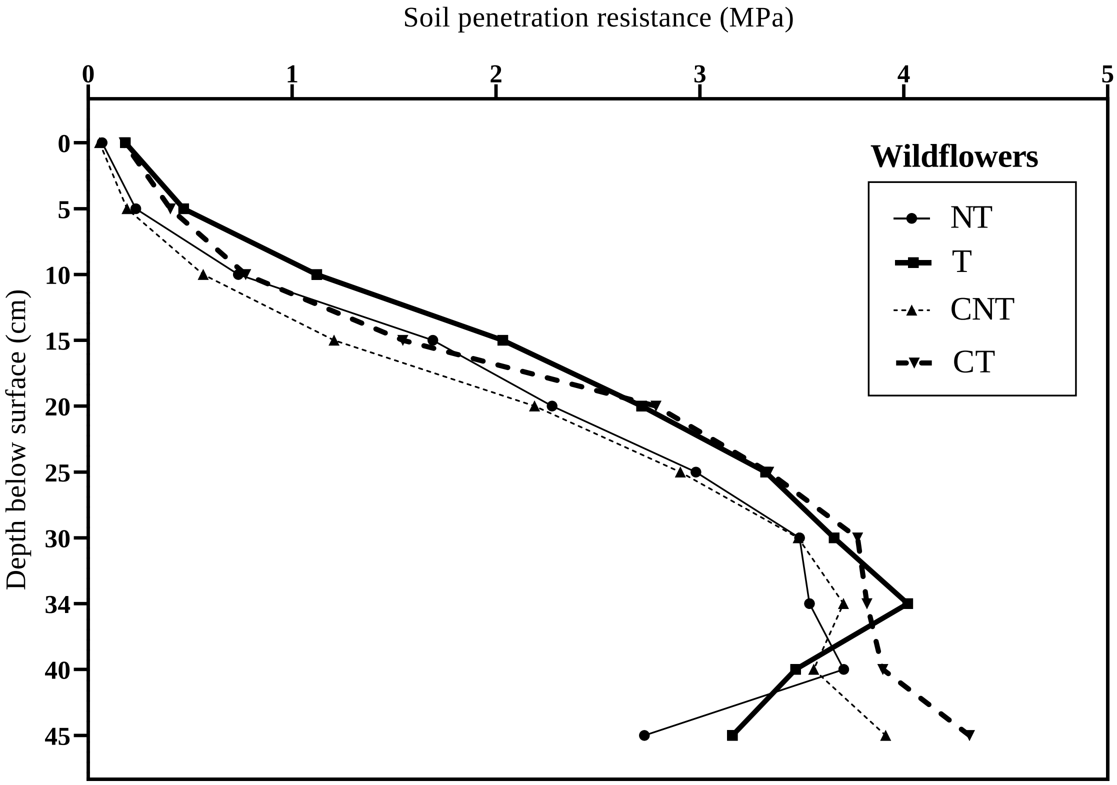

Figure 3.2. Soil penetration resistance versus depth at the Coastal Plain site for wildflowers with no-traffic (NT), traffic (T), compost + no traffic (CNT), and compost + traffic (CT).

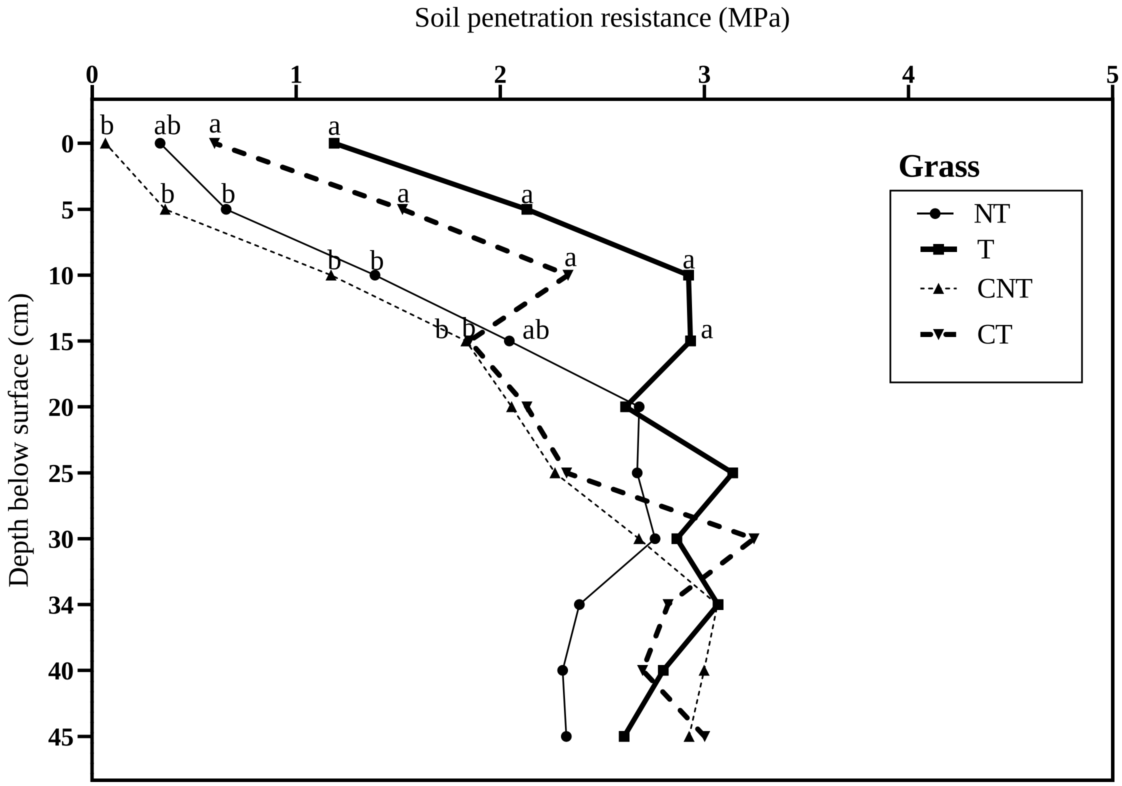

Figure 3.3. Soil penetration resistance versus depth at the Piedmont site for grass with no-traffic (NT), traffic (T), compost + no traffic (CNT), and compost + traffic (CT). Values with the same letter within each depth are not different (p=0.05).

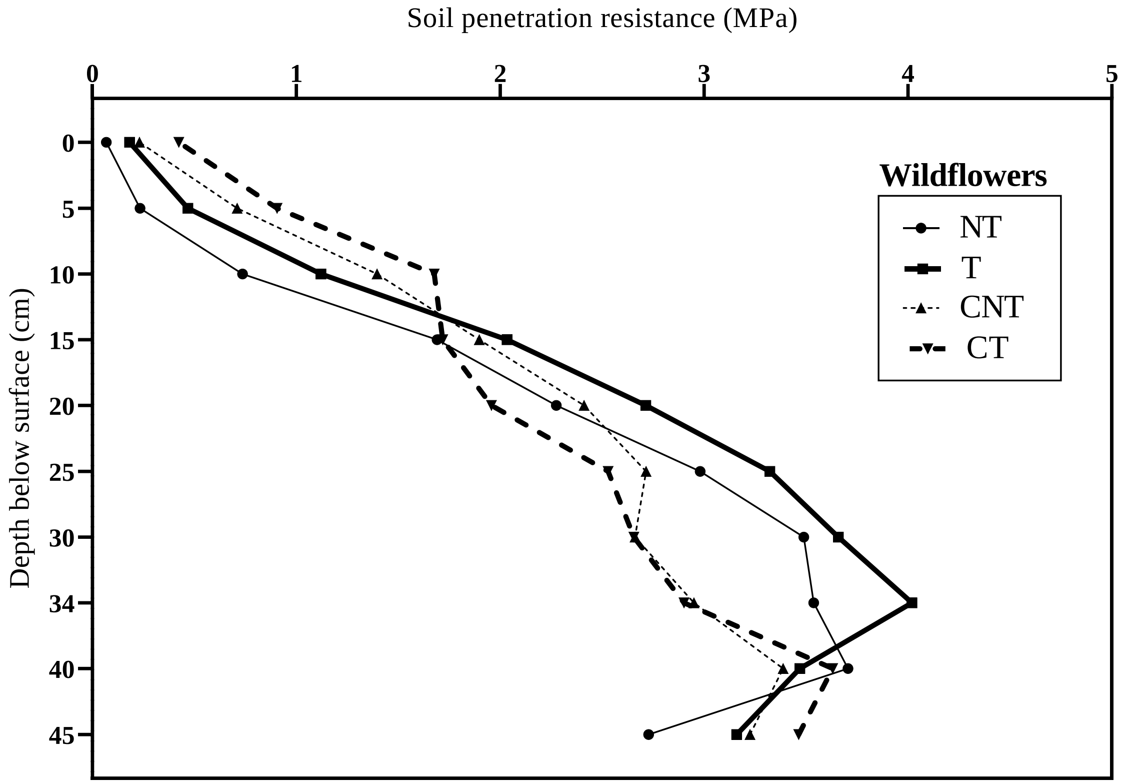

Figure 3.4. Soil penetration resistance versus depth at the Piedmont site for wildflowers with no-traffic (NT), traffic (T), compost + no traffic (CNT), and compost + traffic (CT).

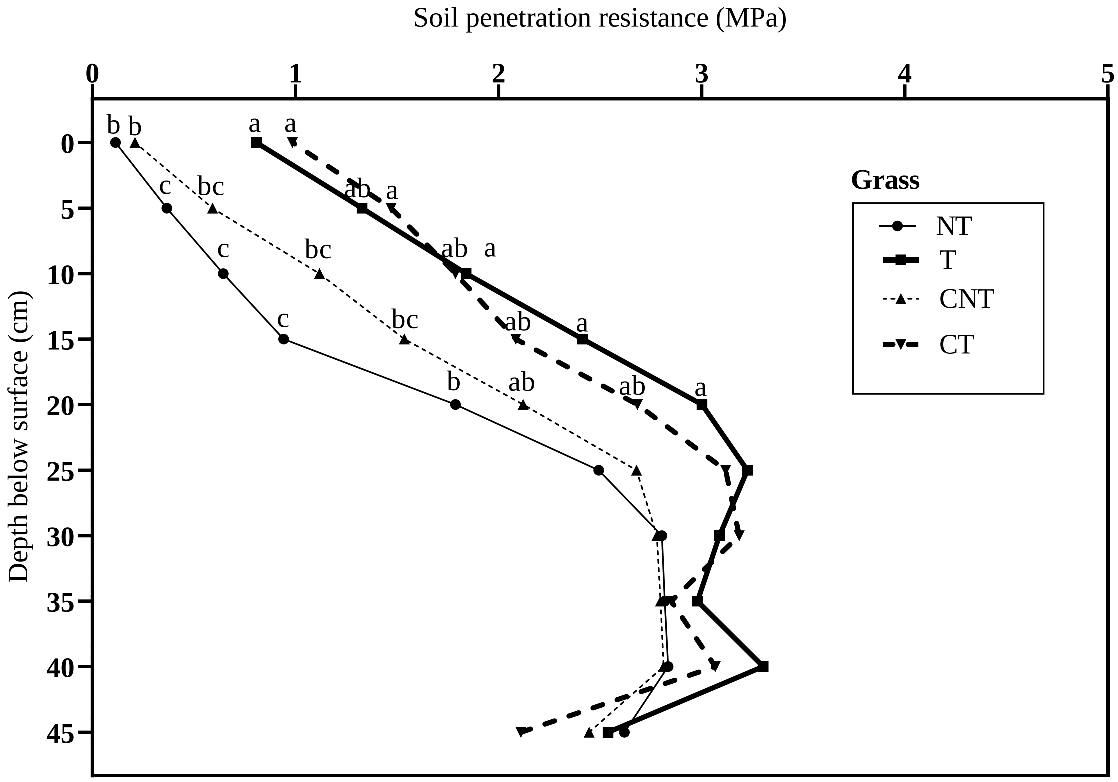

Figure 3.5. Soil penetration resistance versus depth at the Mountain site for grass with no-traffic (NT), traffic (T), compost + no traffic (CNT), and compost + traffic (CT). Values with the same letter within each depth are not different (p=0.05).

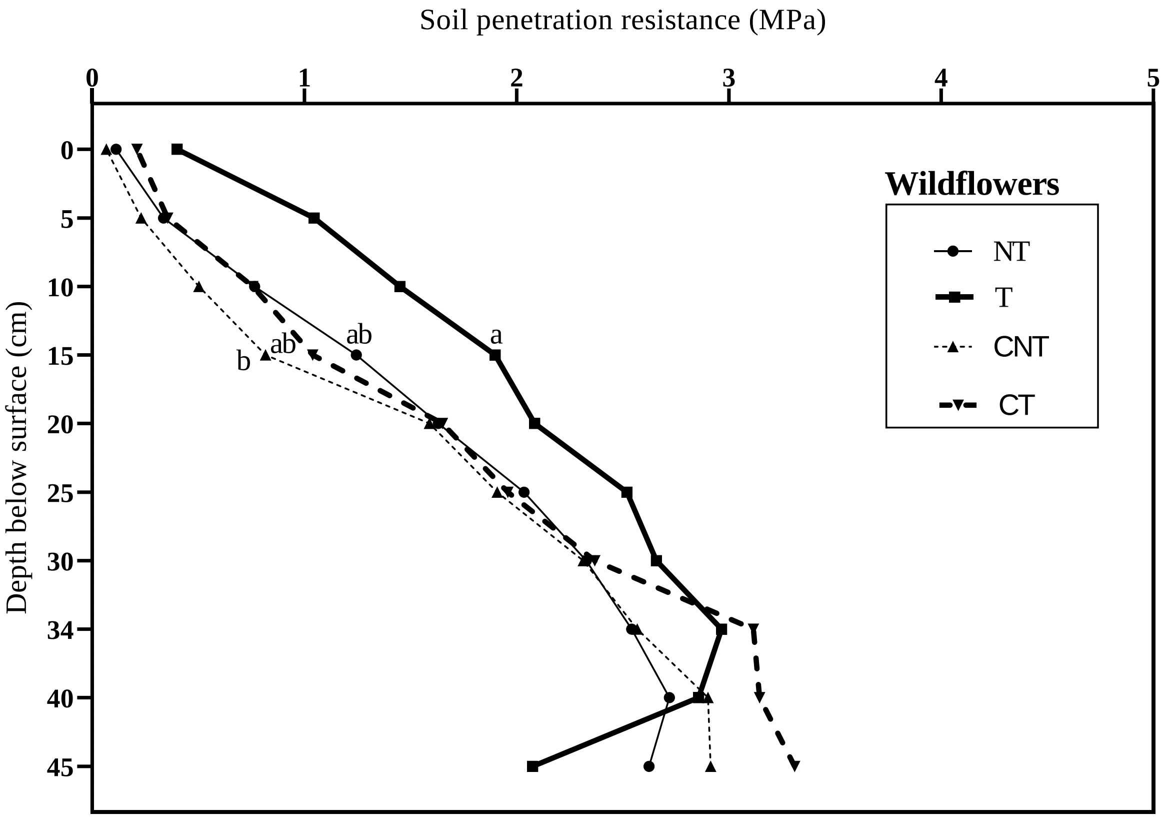

Figure 3.6. Soil penetration resistance versus depth at the Mountain site for wildflowers with no-traffic (NT), traffic (T), compost + no traffic (CNT), and compost + traffic (CT).

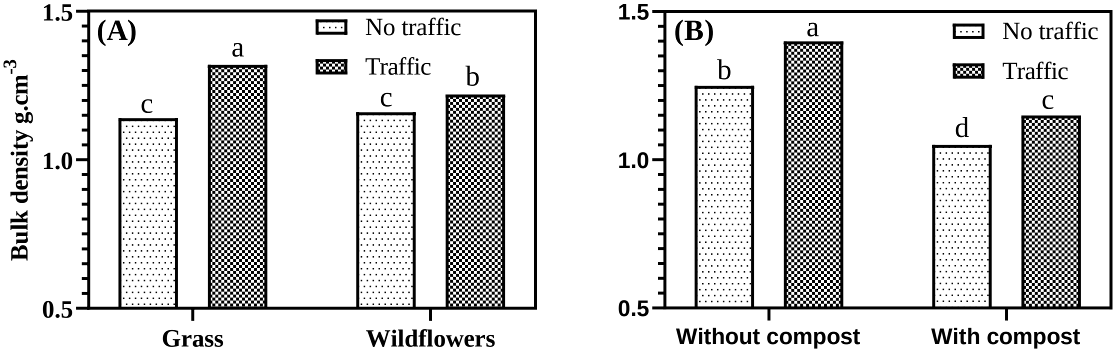

Figure 3.7. Bulk density data collected across locations and years for : A. vegetation x traffic, and B. compost x traffic interaction effects. Values with the same letter are not different (p=0.05).

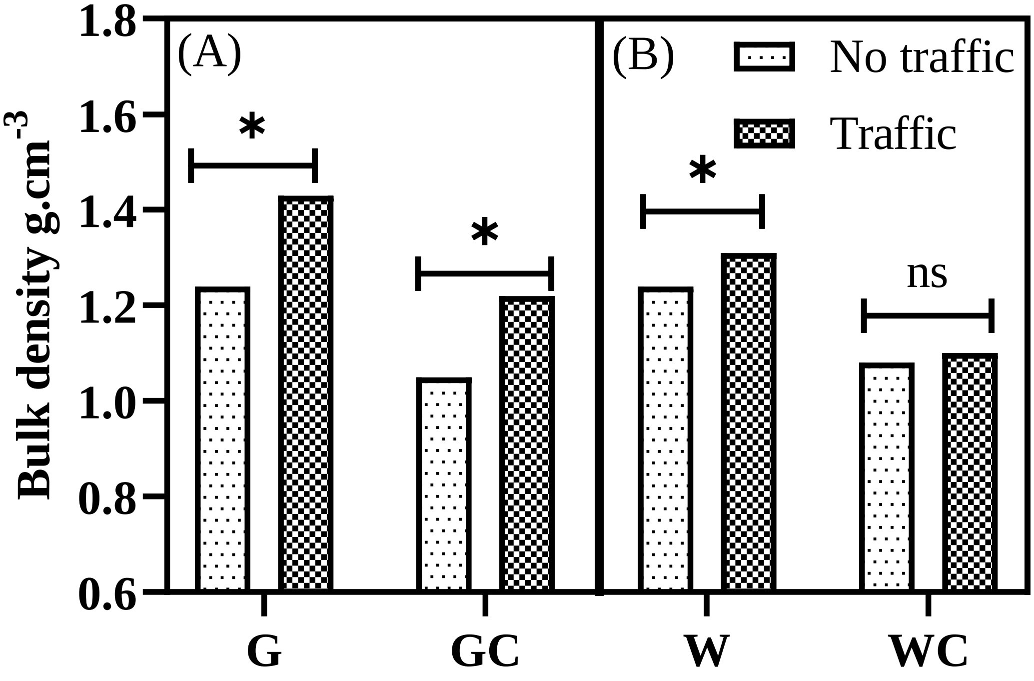

Figure 3.8. Bulk density data collected across locations and years for: A. grass (G) and grass + compost (GC), and B. wildflowers (W) and wildflowers + compost (WC). * denotes significant differences by Fisher's least significant difference (LSD) according to α = 0.05.

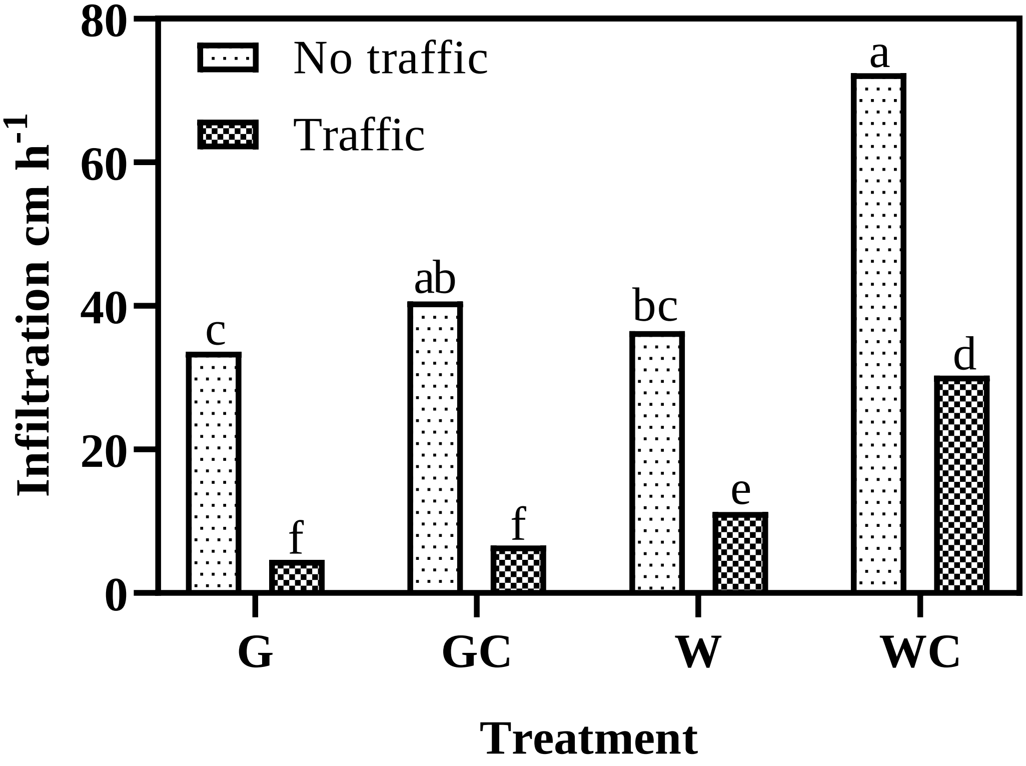

Figure 3.9. Infiltarion data collected across locations and years for grass (G), grass + compost (GC) , wildflowers (W), and wildflowers + compost (WC) under traffic and no traffic. Values with the same letter are not different ($p=0.05$).

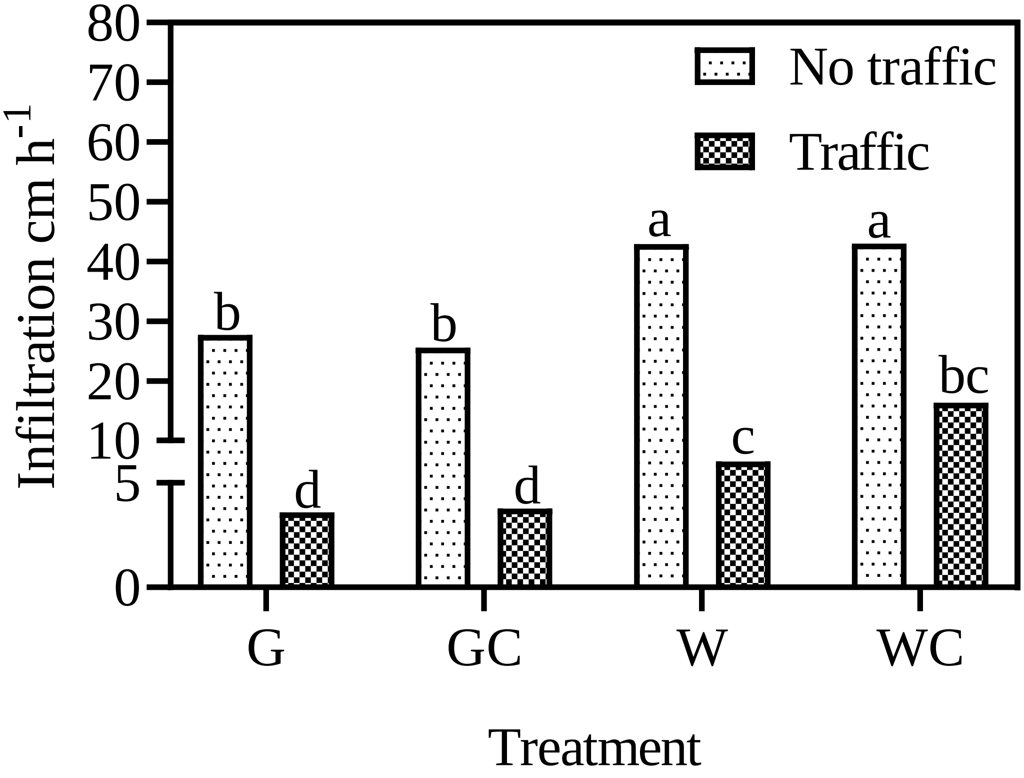

Figure 3.10. Infiltration rate data collected across times at Coastal plain f for grass (G), grass + compost (GC) , wildflowers (W), and wildflowers + compost (WC). Values with the same letter are not different (p=0.05).

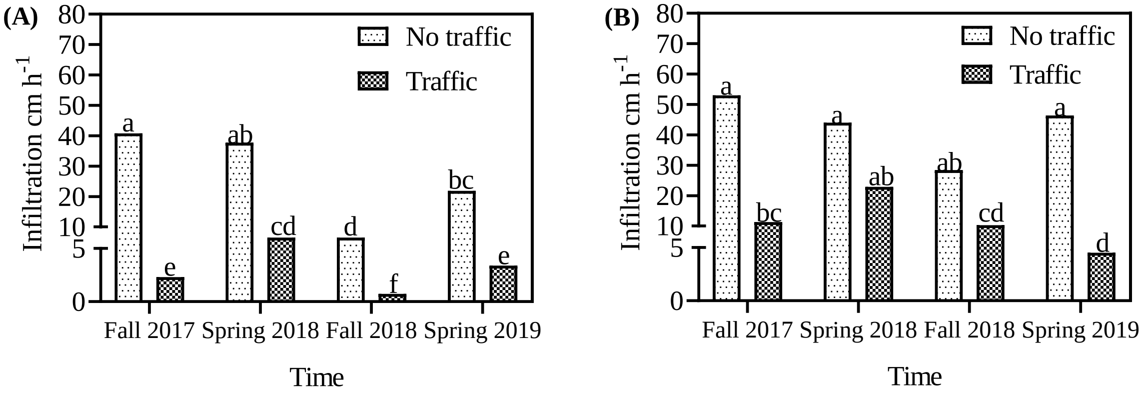

Figure 3.11. Infiltration rate data collected at Coastal Plain for vegetation x traffic interaction effect for (A) grass seasonal infiltration rate, and (B) wildflowers grass seasonal infiltration rate. Same letter within each graph are not different (p=0.05).

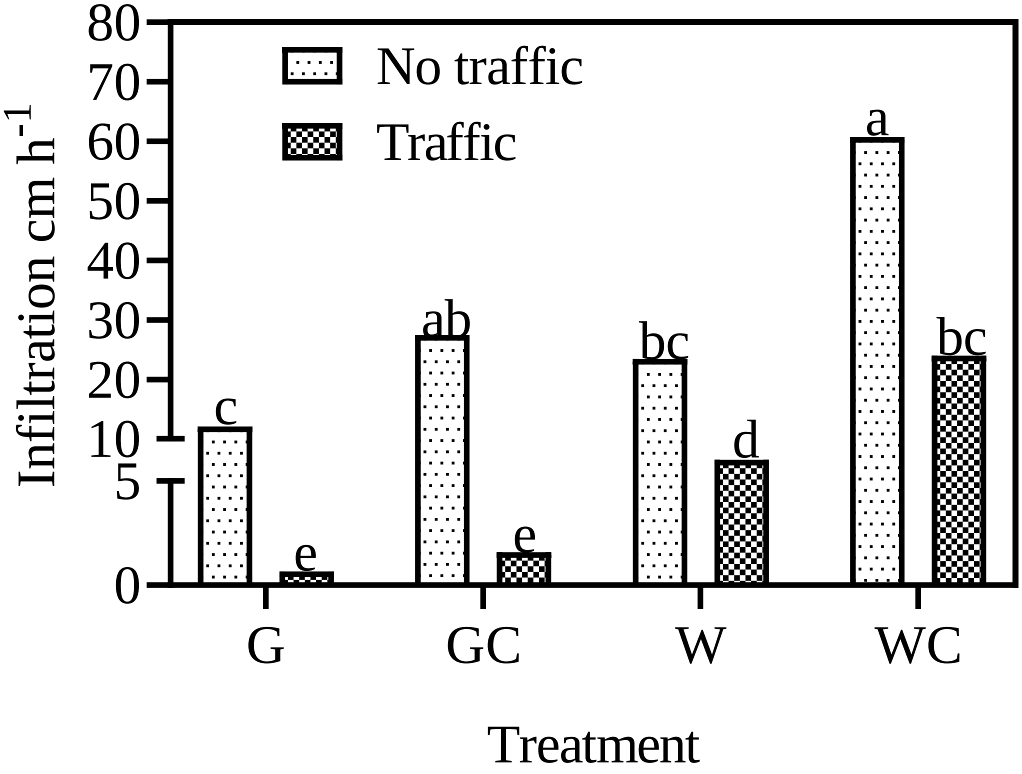

Figure 3.12. Infiltration rate data collected across times at Piedmont for grass (G), grass + compost (GC) , wildflowers (W), and wildflowers + compost (WC). Values with the same letter are not different (p=0.05).

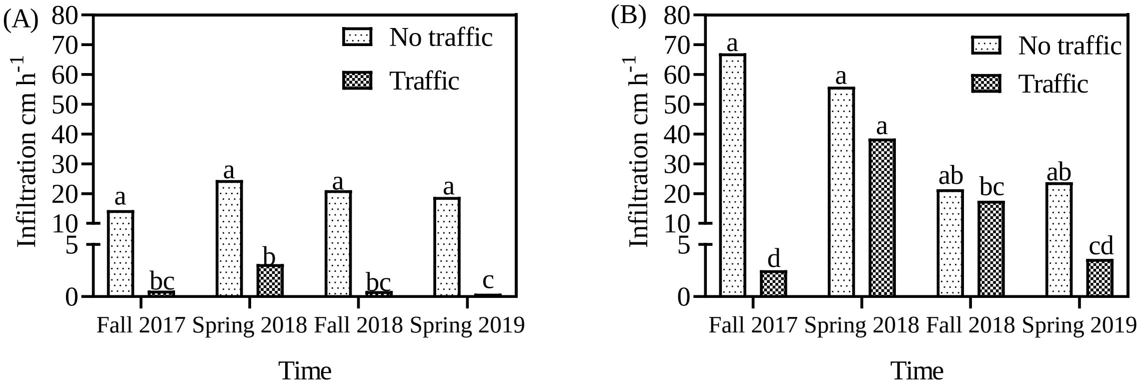

Figure 3.13. Infiltration rate data collected at piedmont for vegetation x traffic interaction effect for (A) grass seasonal infiltration rate, and (B) wildflowers grass seasonal infiltration rate. Same letter within each graph are not different (p=0.05).

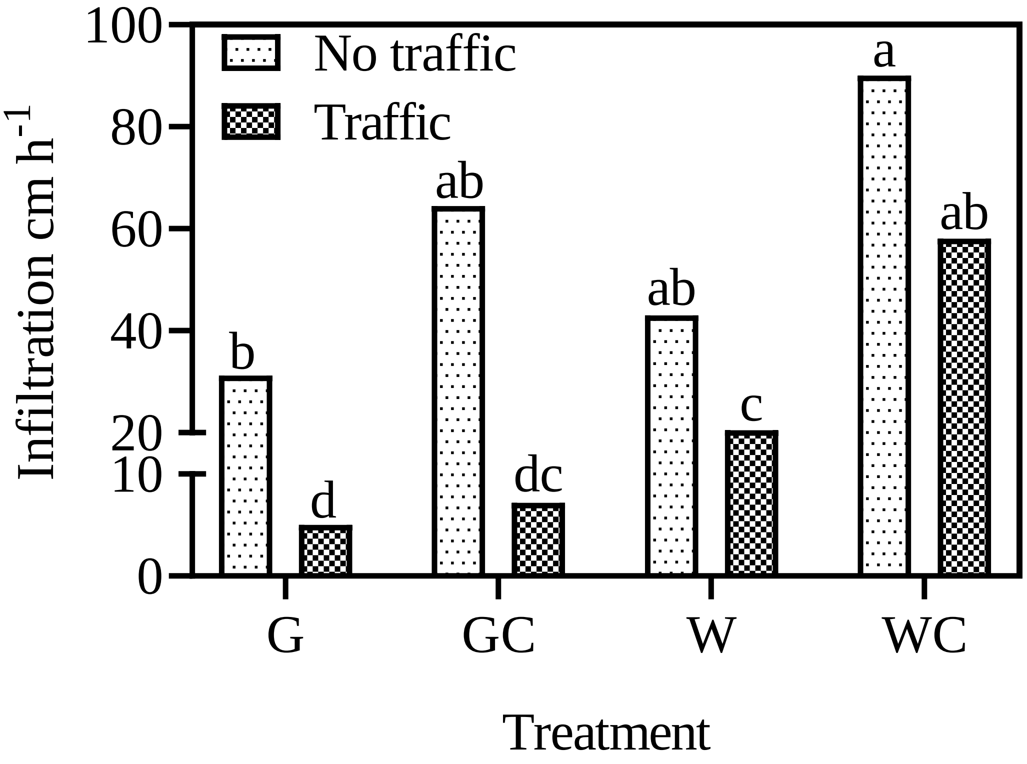

Figure 3.14. Infiltration rate data collected across times at Mountain for grass (G), grass + compost (GC) , wildflowers (W), and wildflowers + compost (WC). Values with the same letter are not different (p=0.05).

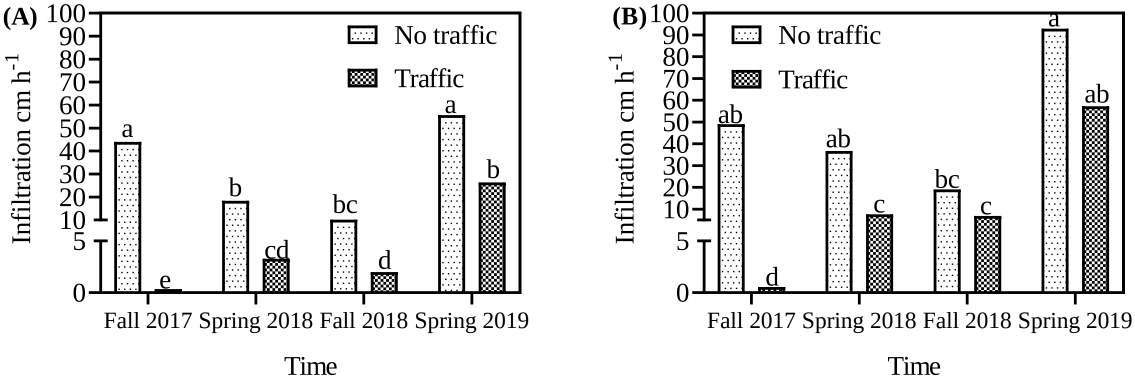

Figure 3.15. Infiltration rate data collected at Mountain for vegetation x traffic interaction effect for (A) grass seasonal infiltration rate, and (B) wildflowers grass seasonal infiltration rate. Same letter within each graph are not different (p=0.05).