ABSTRACT

MOHAMMADSHIRAZI, FATEMEH. Tests of Tillage and Amendments to Remediate Infiltration in Post-Construction Site Soils. (Under the direction of Richard A. McLaughlin and Joshua L. Heitman.)

Constructing roads and buildings often involves removal of topsoil, grading, and traffic from heavy machinery. The result is exposed, compacted subsoil with low fertility and infiltration rate (IR), which hinders post-construction vegetation establishment and generates significant runoff, similar to impervious surfaces. The goal of this project was to assess methods for improving and maintaining perviousness of subsoils compacted by construction equipment. Five sites in North Carolina, USA, were studied to determine the effects of tillage with and without amendments on storm water runoff and sediment loss (at two sites), and soil compaction, IRs and vegetative growth (at all sites) over a period of up to 12 to 32 months, depending on the site. Amendments varied by site and included: compost, cross-linked polyacrylamide, gypsum and lime. At both sites where measured, runoff volume and total amount of soil loss were reduced with tillage by 60-82% during the monitoring period (four months after site establishment). In four out of five sites, tillage significantly decreased soil bulk density (BD) and soil penetration resistance compared to control. Tillage significantly increased IR compared to compacted soil and effects were maintained in most cases for more than two years. Adding compost did not affect IR in most of the tests conducted. Vegetative growth response was inconsistent. A supplementary greenhouse experiment was also conducted to determine the effects of tillage (simulated via BD) on vegetation establishment for species recommended by the NC Department of Transportation and to identify species with potential to increase the soil saturated hydraulic conductivity (K_s) during establishment.

The results showed that compaction level had no species-specific effect on the vegetative growth. The K_s was >10 times greater in the low BD soil compared to high BD, but vegetative growth did not affect K_s at either BD during establishment. Overall, results of these studies suggest that the direct impact of tillage on soil properties (i.e., loosening) is the primary factor affecting increased IR, with vegetation serving primarily to maintain IR over time. Tillage appears to be a viable option for reducing runoff from areas of compacted soils where vegetation will be established post-construction, thereby reducing impacts on stormwater systems and receiving streams.

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Tests of Tillage and Amendments to Remediate Infiltration in Post-Construction Site Soils

by
Fatemeh Mohammadshirazi

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APPROVED BY:

_______________________________ _______________________________

Michael R. Burchell Grady Miller

_______________________________ _______________________________

Joshua L. Heitman Richard A. McLaughlin
Co-Chair of Advisory Committee Co-Chair of Advisory Committee

BIOGRAPHY

Fatemeh Mohammadshirazi was born in Kobe, Japan on July 29, 1985. She got her bachelor degree in the field of Soil Science form University of Tehran, Iran. She continued for a Master degree in the field of Soil fertility and Plant nutrition at that university. Once she got her Master, she received an admission offer from Soil Science Department at the North Carolina State University to continue her education for PhD. Meanwhile, she planned to change her program to Master, thus she got a domination over both soil fertility and physics.

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CHAPTER 1 : EFFECT OF TILLAGE AND COMPOST AMENDMENT ON RUNOFF QUANTITY AND EROSION IN POST CONSTRUCTION SOILS OF THE NORTH CAROLINA PIEDMONT: ESTABLISHMENT

Some data previously presented in V. Brown's thesis (2012) were included for completeness.

Abstract

Soils are compacted during land development through soil excavation and heavy equipment traffic. Compacted soils have limited infiltration and are susceptible to erosion. Infiltration can be enhanced by various approaches including tillage and compost addition. The objective of this study was to determine the efficacy of tillage and adding compost to reduce storm water runoff and sediment loss by improving infiltration in simulated post-construction soils. Tillage treatments were tested at two sites in the Piedmont region of North Carolina (Piedmont 1 and 2). Prior to applying tillage and amendment, soils at both sites were graded to remove the surface horizon and compacted with a vibratory roller. At Piedmont 1 the treatments were: compacted with no tillage, shallow (15 cm depth) tillage (ST), and deep (30 cm depth) tillage (DT). At Piedmont 2 the treatments were: compacted, DT, and DT with incorporated compost (DT+Com). The seeding mixtures recommended by the North Carolina Department of Transportation (NCDOT) for the location (Piedmont) and time of planting were applied at each site. Runoff volumes (RV) and total suspended solids were measured after each of the first 12 and 13 storm events at Piedmont 1 and 2, respectively. Infiltration rate (IR) and bulk density (BD) were determined five and seven months after establishment at Piedmont 1 and 2, respectively. At both sites, RV and total amount of soil loss were reduced with tillage by 60-82% during the monitoring period. Neither deeper tillage nor incorporating compost significantly affected these results. The IRs measured at the end of the monitoring period were around 1 cm h^{-1} in the compacted treatment but ranged from 19-33 cm h^{-1} in the tilled treatments, again with no effects of tillage depth or compost. The results suggest that tillage at the depths of at least 15 cm can be a highly effective method to improve soil conditions and reduce runoff and erosion from highly compacted soils in urbanizing areas.

Key words: compost-construction site-erosion-runoff-tillage

Introduction

The process of constructing roads, buildings, and other structures can result in highly disturbed areas in which the soil is compacted from vehicle and equipment traffic (Gregory et al. 2006). Soils in urban areas may be compacted purposefully to increase strength or unintentionally due to construction activities (Batey and McKenzie 2006; Gregory et al. 2006; Olson et al. 2013). The infiltration rate (IR) in compacted soil in urban areas is low (Brown 2012, Haynes et al. 2013, Siyal 2002, Woltemade 2010, Yang and Zhang 2011), which makes these areas susceptible to erosion and runoff. Areas with compacted soils with low IR can create large amounts of runoff, which is often directed into overburdened storm water systems and stream channels (Booth and Jackson 1997; Violin et al. 2011).

Tillage has successfully reduced soil compaction and improved IR in agricultural settings. Lipiec et al. (2006) showed that tillage affected pore size distribution; 10% of the soil volume contained large pores (>117 μm) in conventional agricultural tillage, while the portion of large pores was 6% in no tillage. The cumulative infiltration using a double-ring infiltrometer on the conventionally tilled treatment for three hours was 94.5 cm, while infiltration in no till treatments was 36-62% less. It may also be possible to implement tillage to improve infiltration for post-construction soil conditions. In a compacted soil simulating post-construction site conditions, Haynes et al. (2013) found that tillage to 20 to 30 cm depth greatly improved infiltration when a vigorous stand of vegetation was established quickly.

Using soil amendments along with tillage might be a way to further improve soil physical properties and plant growth. In a study on a clay loam soil, Bazzoffi et al. (1998) showed that using urban refuse compost along with tillage resulted in reduction of runoff volume (RV) and total erosion during all three years of the experiment. Improved infiltration and changes in saturated hydraulic conductivity were observed in a compost experiment by Curtis et al. (2007). Compost was mixed into a highly erodible, decomposed granite saprolite soil located on a roadside cut slope at three rates: 6%, 12%, and 24% by volume of compost to decomposed granite. Significant increases in saturated hydraulic conductivity were observed at the 12% and 24% compost rates.

Effectively managing storm water RV is a challenge in many urban settings. The objective of this study was to determine the efficacy of soil tillage and compost incorporation to reduce storm water runoff and sediment loss by improving the IR. The study results presented herein represent the first four months after site establishment following treatment at each of two sites.

Materials and Methods

The study was conducted in the Piedmont region of North Carolina, near Raleigh. Two adjacent simulated post-construction sites were evaluated (Piedmont 1 and 2) to study different treatments. Piedmont 1 was established in late February 2011 and Piedmont 2 was established in late April 2012. The sites were located on a grassed slope mapped as Cecil (Fine, kaolinitic, thermic Typic Kanhapludults) and Mantachie (Fine-loamy, siliceous, active, acid, thermic Fluventic Endoaquepts) (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx). Preparation at each site was similar. The topsoil and vegetation were removed to expose the subsoil. Particle size analysis was performed on the exposed subsoil using the hydrometer method (Gee and Bauder 1986). The exposed subsoil contained 48% sand, 12% silt and 40% clay (sandy clay texture). The area was then graded to achieve a uniform surface, with a slope of 2% to allow for some surface drainage.

To simulate compaction from equipment traffic on construction sites, the graded area was further compacted by repeated passes with an 11 Mg (12 ton), smooth drum vibratory roller to obtain a target bulk density (BD) of 1.5 g cm^{-3}. After compaction, BD samples from the upper 10 cm of the soil were taken using a 6-cm diameter soil core sampler (AMS Inc., American Falls, ID, USA). The upper 2.5 cm ring from each sample was discarded to avoid measuring any minor compaction caused by the sampler’s hammer driver. Samples were oven dried at 105 ºC and weighed to determine the BD.

Three tillage treatments were tested at each site with four and three replications at Piedmont 1 and 2, respectively. At Piedmont 1 the treatments were: compacted with no tillage, shallow (15 cm depth) tillage (ST), and deep (30 cm depth) tillage (DT). At Piedmont 2 the treatments were: compacted, DT, and DT with incorporated compost (DT+Com). Compost was an erosion control blend obtained from Novozymes North America, Inc. (Franklinton, NC), with a 1.2 cm sieve size, pH of 7.6 and C:N ratio of 14.5. A 5-cm deep layer of compost was applied to the surface and incorporated during tillage to 15 cm depth. Prior to tilling, a backhoe initially broke up the compacted soil surface to allow the tillage equipment to penetrate to the desired depths. Repeated passes using a tractor-mounted rotary tiller accomplished a tillage depth of approximately 15 or 30 cm, depending on the treatment.

Prior to treatment, soil samples from the upper 10 cm of the site were sent to the North Carolina Department of Agriculture and Consumer Services (NCDA&CS) for analysis for fertilizer and lime recommendations for grass establishment. According to the NCDA&CS recommendation, a commercial 10-20-20 fertilizer was applied at 560 kg ha^{-1} for all treatments. Fertilizer was mixed in during tillage, except for compacted plots where fertilizer was surface-applied. We followed the NC Department of Transportation seeding recommendations and planting dates for the Piedmont region (Roadside Environmental Unit, Vegetation Management, Http://www.ncdot.gov/doh/operations/dp_chief_eng/roadside/ vegetation/). Mixed seed rates of 84.0 kg ha^{-1} hard fescue (*Festuca trachyphylla*), 22.4 kg ha^{-1} Kentucky bluegrass (*Poa pretensis*) and 28.0 kg ha^{-1} rye grain (*Secale cereal*) were used at Piedmont 1, and 73.2 kg ha^{-1} tall fescue (*Festuca arundinacea*), 9.8 kg ha^{-1} centipedegrass (*Eremochloa ophiuroides*) and 29.3 kg ha^{-1} bermudagrass (*Cynodon dactylon*) were used at Piedmont 2. Seed was applied to all plots and protected by temporary cover of straw with jute netting stapled on top at Piedmont 1 (this fabric was removed a few weeks after germination), and straw with a light application of hydromulch at Piedmont 2 (Terra Mulch, Profile Products, Chicago, IL, USA; 1100 kg ha^{-1}). The netting and hydromulch were used to prevent wind from blowing the seed and straw off the plots.

In order to collect runoff, a 1.2 x 1.2 m square and an equilateral triangle with 1.2 m length of each side for Piedmont 1 and 2, respectively, were set at the end of each plot using plastic garden edging (10-cm high) inserted about 5 cm into the soil . The edges and gaps were sealed with expanding foam (Great Stuff, Dow Chemical Company, Wilmington, IL). Along the lower end of the plots, an opening was left, and a 5-cm diameter PVC pipe was sealed flush with the edging. Runoff water generated within the edged area exited via the pipe into a 208 L collection tub, located in a ditch downhill from the plot area. Assuming 100% runoff, the tub size allowed us to capture all runoff from a 36.6 mm storm, which has a recurrence of 0.5 year for a 24-hour period (NOAA Atlas 14. Http://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=nc).To minimize precipitation from increasing runoff volume, each tub was fitted with a lid.

Rainfall data for a weather station adjacent to the sites were retrieved from the State Climate Office of North Carolina (http://www.nc-climate.ncsu.edu). The weather station was located approximately 800 m from the plots. After each storm event, RV was determined by recording the depth of water in the collection tubs and calculating the volume from a calibration curve. Water within the tub was then mixed thoroughly to suspend sediments while a subsample was taken. These subsamples were analyzed for total suspended solids (TSS). If RV was minimal (< 1 L), the entire sample was taken. TSS was determined by filtration (Clesceri et al., 1998) using 90 mm glass fiber filters (ProWeigh, Environmental Express Mt. Pleasant, SC).

Infiltration measurements were obtained using a Cornell Sprinkle Infiltrometer (CSI; Cornell University, Ithaca, NY) at Piedmont 1 and 2 approximately five and seven months after plot installation, respectively. The CSI ring was positioned on ground surface and inserted into the ground to a depth of 7.5 cm so the runoff exit opening on the ring was level with the ground surface. The CSI tank was then filled and placed on top of the ring; a rainfall rate between 20 and 60 cm h^{-1} was set for each plot and allowed to run until a constant rate of runoff was achieved, which typically occurred within 10 minutes. Runoff was collected in a beaker placed in a small hole dug adjacent to the ring, and volume was determined every minute. Lower rainfall rates were used on compacted treatment plots because of the rapid runoff rate in these plots. The IR was calculated from the difference between the water volume applied during the test and the volume of runoff. Correction factors which account for horizontal water movement below the ring were applied to all data according to the CSI manual. At the same time as CSI measurements, additional soil samples were collected from each plot to determine BD, using an approach similar to that described above.

At Piedmont 1, grass establishment sampling was initiated five months after site establishment and seeding (Spring 2011), when the minimum above-ground plant (shoot) height was about 5 to 10 cm. Clippings from inside three randomly selected 10 x 10 cm areas within a 1 x 1 m grid placed on each plot were oven dried at 65ºC for 48 hours and then weighed for above-ground biomass (shoot mass) estimates. Vegetative cover was estimated by taking photos from 1.14 m above each plot with an Olympus digital camera model No.

TG-320 (Olympus Imaging Corp., Tokyo, Japan), then the digital plot photos were analyzed using the Geographic Information System (GIS) program ArcMap (ESRI, Redlands, CA). Images were evaluated for the number of green pixels and the number of non-green pixels to determine grass coverage.

Root samples were obtained for each treatment at Piedmont 1 at approximately the same time as above-ground vegetation was measured. The same AMS soil core sampler used for BD was used to collect samples from two different depths (0 to 15 cm and 15 to 30 cm) for root sampling. The samples were washed to remove the soil from the roots under a steady stream of water using a 1.70 mm U.S.A. standard testing sieve (A.S.T.M.E.-11 specification, Fisher Scientific Company, Chicago, IL). The roots were placed in a paper envelope and oven dried for 48 hours at a temperature of 65ºC. After 48 hours the samples were removed from the oven and equilibrated for few hours to reach room temperature and then weighed.

SAS Software was used to perform all statistical analyses (SAS version 9.1, SAS Institute, Cary, NC). Analysis of Variance (ANOVA) using the PROC MIXED procedure was performed on all data to determine main effects and to separate treatments. Significant differences were measured at $\alpha = 0.05$, unless otherwise noted.

Results and Discussion

Runoff Volume

At Piedmont 1, percentage of rainfall as runoff was less for ST than compacted in seven of 12 storms, and DT had less runoff for all 12 storms compared to compacted

(Table 1.1). Treatment DT had less runoff compared to ST in four events, of which two of these were events with the largest rainfall amounts. This generally supports the idea that deeper tillage can provide greater capacity to infiltrate rainfall and reduce runoff, but that the benefit may only occur for large storms. Over the course of the first 12 storms, almost a third of rainfall ran off the compacted soil and this was reduced by more than 79% with the tillage treatments.

At Piedmont 2, both tillage treatments resulted in reduced runoff in 12 of 13 storms, but there were no significant differences in runoff rates between DT and DT+Com (Table 1.2). Up to 81% of rainfall in individual storms ran off of the compacted treatment, while in all but the first storm less than 10% left the tilled treatments. The overall reduction in RV due to tillage was similar to Piedmont 1, with about 82% less runoff compared to the compacted treatment.

In general, statistical trends between runoff rates and storm total rainfall were weak, likely due to variability in storm duration and soil moisture conditions (data not shown). There were also no clear relationships between runoff rates and peak rainfall intensity, similar to Parsons and Stone (2006). However, for both sites, there was clearly a large reduction in runoff volume in the tilled treatments.

Erosion (Sediment Loss)

At Piedmont 1, sediment loss was less for ST than compacted in five of 12 storms, and DT had less sediment loss in eight of 12 storms compared to compacted (Table 1.1). There were no statistical differences between the two tillage treatments except for one storm, although DT generally had lower total sediment loss values than ST. Total sediment loss was reduced by ST and DT treatments by 64 and 77%, respectively, compared to the compacted treatment. Most of the differences occurred later in the season, perhaps as a result of improved grass growth on the tilled plots, which had significantly higher biomass and vegetative cover (Table 1.3). Greater precipitation totals corresponded to greater sediment loss in compacted ($R^2 = 0.69$), and ST ($R^2 = 0.75$) treatments, but there was weak correlation ($R^2 = 0.32$) in the DT treatment**.** Also, greater peak rainfall intensity corresponded to greater sediment loss in compacted ($R^2 = 0.64$) and ST ($R^2 = 0.64$) treatments but there was no relationship in DT**.** This was likely due to a greater capacity for infiltrating water in DT soil, resulting in a very flat response curve.

At Piedmont 2, erosion was reduced with tillage in four of the 13 events, and reduced during the monitoring period by 60-76% (Table 1.2). There were no statistical differences between DT and DT+Com except for the last storm. There was little relationship between the amount of precipitation and sediment loss at Piedmont 2**.** However, greater peak rainfall intensity corresponded to greater sediment loss in the compacted treatment ($R^2 = 0.72$)**.**

Both sites demonstrated a reduction in erosion losses with tillage, which was closely related to the reduction in RV. The incorporation of 5 cm of compost did not have any impact on erosion, similar to the RV results. While others have demonstrated that rainfall intensity influences erosion rates under simulated conditions (Jennings et al. 1987, McIsaac and Mitchell 1992, Parsons and Stone 2006), we often found weak relationships, particularly for the tilled soils because they generated so little runoff.

Bulk Density and Infiltration Rate

Samples taken after compaction had an average BD of close to 1.5 g cm^{-3} in the upper 15 cm at both sites. Other studies related to construction operations also reported similar values for soil with a significant amount of clay (Alberty et al. 1984, McNabb 1994, Yang and Zhang 2011). At Piedmont 1, tillage reduced soil BD to 1.35 and 1.25 g cm^{-3} for ST and DT, respectively, five months after site establishment (Table 1.4). At Piedmont 2, tillage reduced BD to 1.02 and 0.66 g cm^{-3} for DT and DT+Com, respectively, seven months after site establishment (Table 1.5). Numerous studies have documented the decrease in BD as a result of tillage in agricultural settings (e.g., Chen et al. 2010, Islam et al. 1994).

The compacted treatment had relatively low IR of 2.1 and 0.9 cm h^{-1} at Piedmont 1 and 2, respectively (Table 1.4 and Table 1.5). In contrast, the tillage treatments improved the IR to 19.8-33.3 cm h^{-1}. Neither the depth of tillage nor the addition of compost affected infiltration. We do note that when using a single-ring apparatus, the potential lateral flow of infiltrating water below the ring may increase the apparent IR on unsaturated soils. Lateral flow toward drier areas of the soil pulls water from the surface towards areas outside the ring. Thus, the estimates of the steady IR in may be somewhat larger than those expected for natural storm. To minimize the effect of lateral flow in our data, a correction factor was used according to CSI manual. However, the measurements do demonstrate the relative effects of the tillage treatments compared to the compacted soil. An infiltration survey by Yang and Zhang (2011) found similarly low IR in urban areas, 6.3 cm h^{-1} to less than 0.1 cm h^{-1}. Other studies have also shown low infiltration due to compaction (Siyal 2002; Woltemade 2010). Haynes et al. (2013) found that IRs were < 0.1 cm h^{-1} in similar soil compacted by truck traffic. At an agricultural site, Lipiec (2006) measured at 61% increase in infiltration after tillage, which is comparable though somewhat less than what we observed.

Plant Growth

At Piedmont 1, five months after site establishment, tillage significantly improved grass growth (Table 1.3). The shoot masses for the tilled treatments were almost two times greater than for compacted. Similarly, grass coverage was 42% on compacted compared to 62% and 56% for ST and DT, respectively. No vegetation data were collected at Piedmont 2, but photographs taken three months after site establishment illustrate that there was a strong grass response to tillage and compost compared to the compacted plots (Figure 1.1).

At Piedmont 1, five months after site establishment, in depths of 0 to 15 cm, the root density was greater in DT compared with both compacted and ST (Table 1.6). At the 15 to 30 cm depth, ST and DT both increased root density compared with compacted. Consistent with these results, Grzesiak et al. (2002) showed that soil compaction is one of the most important factors of reducing root system development. Varsa et al. (1997) found that tillage caused greater depths of rooting in the profile. In general, the tilled treatments had good grass establishment. Good vegetation establishment plays an important role in controlling runoff volume and sediment loss by stabilizing the soil (Marques et al. 2007; Pan and Shangguan 2006). Pan and Shangguan (2006) found that soils with vegetative cover (35%, 45%, 65% and 90%) reduced runoff by 14–25% and sediment loss by 81–95% compared to bare soil.

Summary and Conclusions

Post-construction soils often have limited infiltration and greater runoff rates during storm events. Tillage mechanically breaks up the soil, immediately adding porosity for rapid transfer of water through the soil profile. Both deep and shallow tillage treatments reduced runoff during the first four months after site establishment when the grass was being established, and there was some evidence that deeper tillage provided increased rainfall capture capacity. Deep tillage resulted in substantial infiltration, 87 to near 100% of precipitation, during all storm events compared to as low as 19% in the compacted soils. The results from this study indicate that when tillage is implemented on a modest slope, a large increase in infiltration and corresponding reduction in soil loss can result. This study explored one way to mitigate urban stormwater volume problems. By increasing the IR through tillage and a healthy vegetative cover, soil may become a primary component of a storm water management system.

Tables and Figures

Table 1.1 Rainfall, peak intensity, runoff and sediment loss at Piedmont 1 for 12 storms that generated runoff immediately after establishment. The site was established in late February 2011.

Treatments	Storm Date (2011)												
	6-Mar	9-Mar	26-Mar	5-Apr	9-Apr	16-Apr	28-Apr	4-May	14-May	31-May	20-Jun	27-Jun	Total
	Precipitation (mm)												
	22	14	9	11	33	16	13	12	19	30	15	51	245
	Peak Storm Intensity (mm h^{-1})												
	12	3	2	6	11	11	8	4	17	19	11	42	
	Runoff (% of rainfall)												
Compacted	22 a	8a	32a	26a	76a	61a	19a	6a	57a	26a	6a	40a	32a
Shallow till	0.6b	2b	17a	5a	13b	6b	3b	2ab	9b	6ab	2ab	13b	7b
Deep till	1b	0.6b	2b	1b	2c	3b	2b	1b	4b	3b	2b	3c	4b
	Sediment Loss (kg ha^{-1})												
Compacted	37a	2.7a	134a	16a	158a	71a	25a	14a	89a	94a	40a	288a	969a
Shallow till	46a	1.9ab	5a	21a	57a	31b	31a	10ab	13b	19b	7b	103b	345b
Deep till	45a	1b	11a	9.5b	53a	16b	14a	6b	14b	19b	10b	26b	225b

Note: Means followed by the same letter within a column and at a given site are not statistically different (p=0.05).

Table 1.2 Rainfall, peak intensity, runoff and sediment loss at Piedmont 2 for 13 storms that generated runoff immediately after establishment. The site was established in late April 2012.

Treatments	Storm Date (2012)													
	5-May	9-May	14-May	17-May	22-Jun	10-Jul	11-Jul	20-Jul	23-Jul	28-Jul	7-Aug	22-Aug	3-Sep	Total
	Precipitation (mm)													
	33	18	16	13	14	16	18	17	19	23	16	9	34	245
	Peak Storm Intensity (mm h^{-1})													
	14	15	5	12	6	12	10	4	18	22	12	8	23	
	Runoff (% of rainfall)													
Compacted	51a	61a	45a	81a	1a	5a	22a	27a	14a	25a	21a	36a	30a	33a
Deep till	11b	6b	5b	4b	1a	1b	2b	1b	2b	9b	2b	5b	5b	5b
Deep till+compost	13b	7b	3b	4b	1a	1b	2b	2b	3b	9b	4b	8b	7b	6b
	Sediment Loss (kg ha^{-1})													
Compacted	53a	37a	44a	194a	0.9b	12a	31a	15a	27a	48a	12a	8a	20ab	502a
Deep till	17b	12a	7b	18b	3a	6a	3a	1b	9a	19a	5a	9a	11b	120b
Deep till+compost	21b	15a	2b	24b	1.2ab	6a	5a	2b	15a	48a	8a	17a	38a	202b

Note: Means followed by the same letter within a column and at a given site are not statistically different (p=0.05).

Table 1.3 Dry shoot mass and grass coverage at Piedmont 1, five months after site establishment.

Treatment	Shoot mass (kg ha^{-1})	Grass cover (%)
Compacted	946b	42b
Shallow till	1,597a	62a
Deep till	1,566a	56a

Note: Means followed by the same letter within a column are not statistically different (p=0.05).

Table 1.4 Infiltration rates and bulk density at Piedmont 1, five months after site establishment.

Treatment	Bulk Density (g cm^{-3})	Infiltration Rate (cm h^{-1})
Compacted	1.49a	2.1b
Shallow till	1.35b	20.8a
Deep till	1.25b	21.8a

Note: Means followed by the same letter within a column are not statistically different (p=0.05).

Table 1.5 Infiltration rates and bulk density at Piedmont 2, seven months after site establishment.

Treatment	Bulk Density (g cm^{-3})	Infiltration Rate (cm h^{-1})
Compacted	1.48a	0.9c
Deep till	1.02b	19.8b
Deep till + compost	0.66c	33.3a

Note: Means followed by the same letter within a column are not statistically different (p=0.05).

Table 1.6 Root density at Piedmont 1, five months after site establishment.

Treatment	Root density (kg m^{-3})	
	0-15 cm	15-30 cm
Compacted	0.43b	0.01b
Shallow till	0.56b	0.18a
Deep till	1.07a	0.21a

Note: Means followed by the same letter within a column are not statistically different (p=0.05).

Figure 1.1 Plots at Piedmont 2 after three months, showing grass response to compacted (on the right), tillage alone (on the left) and part of the tillage+compost plot (on the far left end).

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CHAPTER 2 : EFFECT OF TILLAGE AND AMENDMENTS ON SOIL COMPACTION, VEGETATIVE GROWTH AND INFILTRATION RATE FOR SOILS DISTURBED THROUGH DEVELOPMENT

Some data previously presented in V. Brown's thesis (2012) were included for completeness.

Abstract

Constructing roads and buildings often involves removal of topsoil, grading, and traffic from heavy machinery. The result is exposed, compacted subsoil with low fertility and infiltration rate (IR), which hinders post-construction vegetation establishment and generates significant runoff, similar to impervious surfaces. The goal of this project was to assess methods for improving and maintaining perviousness of subsoils compacted by construction equipment. The objective of this study was to evaluate effects of tillage with and without amendments on (1) soil compaction, (2) IR, and (3) vegetative growth over a period of up to 32 months. Five sites in North Carolina, USA, were studied, one each in the Sandhills and Mountain regions and three in the Piedmont region, to evaluate effects of tillage with and without amendments on soil compaction, IRs and vegetative growth over a period of 12 to 32 months, depending on the site. Amendments varied by site and included: compost, cross-linked polyacrylamide (xPAM), gypsum and lime. At four sites, the topsoil was removed and the subsoil compacted with a vibratory roller prior to the treatment. At the fifth site, fill soil was added to a depth of 30 cm and then compacted as at the other sites. A soil core sampler and a penetrometer were used for the soil bulk density (BD) and soil penetration resistance

(SPR) measurements, respectively. IR were conducted using a Cornell Sprinkle Infiltrometer. The Geographic Information System (GIS) was used to analyze the digital photos of the plots to measure the vegetative cover. Root measurements were made using a soil core sampler. Tillage significantly decreased soil compaction (BD and SPR) compared to the compacted soil in all sites except at the fill site. Applying compost prior to tillage reduced BD at two of four sites where it was tested. Tillage significantly increased the IR compared to compacted soil and the effects were maintained in most cases for more than two years. Steady IRs of up to 30 cm h^{-1} were measured when tillage was implemented, and the IRs were maintained at >2 times that of the compacted soil over the monitoring period. Adding amendments did not have any effect on IR except at the fill site, which compost and xPAM started affecting IR before 12 months after site establishment. The vegetative growth response (shoot mass, vegetative cover and root mass) was inconsistent and did not have any effect on IR. The results suggest that the direct impact of tillage on soil properties (i.e., loosening) may be the primary factor affecting increased IR, with vegetation serving primarily to maintain IR over time. Tillage appears to be a viable option for reducing runoff from areas of compacted soils where vegetation will be established post-construction, thereby reducing impacts on stormwater systems and receiving streams.

Key words: infiltration rate-soil compaction-tillage-vegetative growth

Introduction

Soil can become compacted during construction activities, whether intentionally to increase soil strength or unintentionally by traffic of heavy equipment (Batey and McKenzie 2006; Gregory et al. 2006; Olson et al. 2013).

Compaction affects soil physical properties and vegetative growth (Randrup and Dralle 1997). Several studies found that compaction reduced soil porosity (Craul 1994; Schafer-Landefeld et al. 2004; Shestak and Busse 2005) and infiltration rate (IR) (Siyal 2002; Woltemade 2010) and this lead to high amount of runoff and erosion (Booth and Jackson 1997; Violin et al. 2011). Yang and Zhang (2011), showed that IR in many developed areas is low, and less than 1 mm h^{-1} in some cases. Other studies showed that compaction reduced root growth (Alberty et al. 1984; Gilman et al. 1987).

Creating an environment for plant roots to grow deeper is important because plants with shallow roots are more susceptible to drought stress and lack of deep rooting limits development of channels for water infiltration (Bartens et al. 2008; Bouma and Dekker 1978; Hino et al. 1987).

One best management practice (BMP) for controlling erosion in post-construction sites (after all construction activities are done) is to use tillage to increase IR and vegetation establishment, which decreases stormwater runoff and increases overall soil health (Haynes et al. 2013; Olson 2013). Lipiec (2006) documented that tillage successfully reduced soil compaction and improved IR in agricultural settings.

Using soil amendments along with the tillage might be a good way to improve soil physical properties and plant growth. In one study Bazzoffi et al. (1998) showed that amending clay loam soil with compost increased IR, decreased the runoff volume, and reduced the erosion. Cross-linked polyacrylamide (xPAM) also can be used as amendment to reduce soil penetration resistance (SPR) and it increases water holding capacity. Busscher et al. (2009) found that using xPAM with tillage reduced SPR and decreased soil compaction more than tillage alone. Studies have shown that gypsum can reduce SPR in soil (Ellington 1986; Radcliffe et al. 1986) and that it can also increase aggregate stability and preserve soil porosity (Buckley and Wolkowski 2014). Other studies showed that application of gypsum can increase IR in soil and reduce erosion (Amezeketa et al. 2005, Yu et al. 2003).

Soil improvement practices, such as tillage and amendments, are not commonly applied on post-construction sites. This study links all of these practices side by side to investigate the effects of them on the infiltration improvement in compacted soils and if there is any effect, how long it will remain on the sites. The objective of this study was to evaluate effects of tillage with and without amendments on (1) soil compaction, (2) IR and (3) vegetative growth over a period of up to 32 months.

Materials and Methods

Study Area

This study had locations in each of three North Carolina soil regions (Table 2.1): Two cut sites, where the topsoil was removed and the subsoil was compacted, were located in the

Sandhills (Jackson Springs, NC) and Mountain (Mills River, NC) regions (hereafter, Sandhills and Mountain, respectively). Two additional cut and one fill sites, for which 30 cm of a soil from a different location was put on top of the existing exposed subsoil and compacted, were located in the Piedmont (Raleigh, NC) region (hereafter Piedmont 1 [cut], Piedmont 2 [cut], and Piedmont 3 [fill], respectively). The Sandhills and Mountain sites were both established in August 2011, Piedmont 1 in February 2011, Piedmont 2 in April 2012, and Piedmont 3 in October 2013.

Cut Site Preparation

Preparation at each of the four cut sites was similar. The topsoil and vegetation were removed to expose the subsoil. The area was then graded to achieve a uniform surface and with a slope of 5% or less for drainage. To simulate compaction during construction activities, the graded area was compacted by repeated passes with a smooth drum vibratory roller (eight ton Sandhills, 10 ton Mountain, 12 ton Piedmont). Before performing any tillage, the soil was loosened by a backhoe to either 15 or 30 cm (at Sandhills a multi-shank subsoiler/ripper was used), followed by a tractor-mounted rotary tiller for tillage to the target depths.

Fill Site Preparation

For preparing the fill site (Piedmont 3), approximately 30 cm of local fill soil was added to an area where topsoil had previously been removed, and the fill material was subsequently compacted using a 12-ton, smooth drum vibratory roller. In contrast to the other sites, a backhoe was not needed to break up soil and tillage was directly applied using a tractor-mounted rotary tiller.

Treatments, Plot size, Replications

For all except Piedmont 2 and Piedmont 3 sites, three tillage treatments were assigned, including: compacted with no tillage, shallow tillage (15cm; ST), and deep tillage (30cm; DT) (Table 2.2). For Piedmont 2 and Piedmont 3, the tillage treatments were compacted and DT only. Different amendments were applied in combination with tillage at different sites and included: compost, xPAM, gypsum, and lime (Table 2.2). Compost, obtained from Novozymes North America Inc. (Franklinton, NC) and made of fermented sawdust, tree/shrub trimmings, leaves, wood chips and pine straw (Erosion Control 1.2 cm sieve size, pH 7.6, C:N 14.5), was used for Sandhills, Mountain, and Piedmont 2. Compost, obtained from the City of Raleigh (NC) and made of yard wastes such as grass clippings, shrubbery trimmings, leaves, limbs, logs, brush, pine straw, and hay (pH 6.8, C:N 31.1), was used for Piedmont 3. The xPAM was Aquasorb (SNF Inc., Riceboro, GA) for the Mountain site, and Stockosorb (Evonik Corporation, Greensboro, NC) for the Piedmont 3 site. Pelletized gypsum was used at Piedmont 3.

Plots at all sites except Sandhills and Piedmont 3 were divided into subplots to determine the extent of compaction from wheel traffic. Grass was cut using either a riding lawn mower (John Deere 455, 90 kPa at Mountain and John Deere 777 Ztrak, 177 kPa at Piedmont 1 and 2) to represent “traffic” or a string trimmer to represent “no traffic.”

The experimental design of the main plots for all sites was a randomized complete block design (RCBD). All sites had four replications except Piedmont 2, which had three. Main plot sizes were 4.6 x 6 m at both Sandhills and Mountain. At Piedmont 1, the main plot sizes were 3.6 x 6 m for ST and compacted, and 4.3 x 6 m for DT. At Piedmont 2, the main plots were 1.5 x 3 m and at Piedmont 3 were 3 x 6 m.

Fertilizer Application and Seeding

Particle size analysis (Table 2.1) was performed on soil samples from each site using the hydrometer method (Gee and Bauder 1986). Soil samples from each site were sent to the North Carolina Department of Agriculture and Consumer Services (NCDA&CS) for turf fertilizer and lime recommendations (Table 2.1). Fertilizer was mixed in during tillage, except for compacted plots where fertilizer was surface-applied. Fertilizer recommended by NCDA&CS was mixed in during tillage, except for compacted plots where fertilizer was surface-applied.

The following seeding mixtures recommended by the North Carolina Department of Transportation (NCDOT) for the location and time of planting were applied at each site (NCDOT 2008): tall fescue (*Festuca arundinacea*) and bermudagrass (*Cynodon dactylon*) at the Sandhills site; tall fescue at the Mountain site; Kentucky bluegrass (*Poa pretensis*), hard fescue (*Festuca trachyphylla*), and rye grain (*Secale cereal*) at Piedmont 1; tall fescue, bermudagrass and centipedegrass (*Eremochloa ophiuroides*) at both Piedmont 2 and Piedmont 3. Rates for each seeding mixture are listed in Table 2.3.

After seeding, the plots were temporarily covered with different materials depending on the site. The materials were: 3400 kg ha^{-1} of straw which was held in place by thin twine stretched across the plot and stapled in the ground at Sandhills; 3300 kg ha^{-1} of straw at Mountain; 4500 kg ha^{-1} of straw covered with sheets of woven jute fabric and stapled to the ground (this fabric was removed a few weeks after germination) at Piedmont 1; straw with a light application of hydromulch at Piedmont 2 (Terra Mulch, Profile Products, Chicago, IL, USA; 1100 kg ha^{-1}); and straw blankets stapled to the ground at Piedmont 3. The netting and hydromulch were used to prevent wind from blowing the straw off of the plots.

Plots were reseeded with tall fescue at 145, 240 and 73.2 kg ha^{-1} at six, seven and one months after site establishment at Sandhills, Piedmont 1 and Piedmont 3, respectively, to improve stand density. Piedmont 3 was also reseeded again with tall fescue (73.2 kg ha^{-1}), bermudagrass (29.3 kg ha^{-1}) and centipedegrass (9.8 kg ha^{-1}) at six months after site establishment.

Each site was fertilized with additional nitrogen (N) at differing rates and periods of time after establishment. A rate of 50 kg ha^{-1} of N was applied to Sandhills six months after establishment, 5 kg ha^{-1} of N was applied to Mountain seven months after establishment, and 50 kg ha^{-1} of N was applied to Piedmont 1 seven months after establishment. At Sandhills, 100 kg ha^{-1} of potassium (K) also was added to the plots six months after site establishment.

Soil Compaction Measurement

Bulk density (BD) samples from the upper 10 cm of soil were taken using a 6-cm diameter core sampler (AMS Inc., American Falls, ID, USA) after initial compaction and before the treatment establishment. The upper 2.5 cm ring from each sample was discarded to avoid measuring any minor compaction caused by the sampler’s hammer driver. Samples were oven dried at 105 ºC and weighed to determine BD. Samples were then taken periodically for up to 12 to 32 months after the treatment establishment, using the same approach, at all sites to document changes.

SPR from 0 to 30 cm soil depths was also measured at each site (the time of measurement differed depending on the site) using a cone tipped penetrometer (FieldScout SC 900 Soil Compaction Meter, Spectrum Technologies Inc.). The SPR measurements were conducted at three different areas of each individual plot.

Infiltration Rate Measurement

A Cornell Sprinkle Infiltrometer (CSI), (Cornell University, Ithaca, NY) was used to estimate IR over a period of 12 to 32 months, depending on the site, after the tillage treatments were applied. Permanent infiltration rings were installed at Piedmont 3 while temporary rings were installed in different locations within the plots for the other sites. The CSI ring was positioned on the ground surface and inserted into the ground to a depth of 7.5 cm, where the runoff exit opening on the ring was level with the ground surface. The CSI was then filled with water and placed on top of the ring; a rainfall rate between 20 and 60 cm h^{-1} was set for each plot and allowed to run until a constant rate of runoff was achieved, which typically occurred within 10 minutes. Runoff was collected in a beaker placed in a small hole dug adjacent to the ring, and volume was determined every minute. Lower rainfall rates were used on the compacted treatment plots to reduce runoff volume. The IR was measured as the difference between the water volume irrigated during the test and the volume of runoff. The correction factors which account for horizontal water movement at the bottom of the ring were applied to all data according to the CSI manual.

Plant Growth Measurement

Grass establishment sampling at each site was initiated when the minimum blade length was about 5-10 cm. Clippings from inside three randomly selected 10 x 10 cm areas within a 1 x 1 m grid placed on each plot were oven dried at 65ºC and weighed for shoot mass estimates. Vegetative cover was estimated by taking photos from 1.14 m above each plot with an Olympus digital camera model No. TG-320 (Olympus Imaging Corp., Tokyo, Japan), then the digital plot photos were analyzed using the Geographic Information System (GIS) program ArcMap (ESRI, Redlands, CA). Images were evaluated for the number of green pixels and the number of non-green pixels to determine vegetative cover.

Root measurements were made for each treatment at all Piedmont sites at approximately the same time as above-ground vegetation was measured. The AMS soil core sampler used for BD was used to collect samples from two different depths (0 to 15 cm and 15 to 30 cm) for Piedmont 1 and Piedmont 2 for rooting measurements. At Piedmont 3, root sampling was done by core sampler at depths of 0 to 7.5 cm, 7.5 to 15 cm, and 15 to 23 cm. The samples were washed to remove the soil from the roots under a steady stream of water using a 1.70 mm U.S.A. standard testing sieve (A.S.T.M.E.-11 specification, Fisher Scientific Company). The roots were placed in the paper envelopes and oven dried for 48 hours at a temperature of 65ºC. After 48 hours the samples were removed from the oven and equilibrated for few hours to reach the room temperature and then weighed.

Statistical Analysis

Analyses of variance were performed on the dependent variables of BD, SPR, IR, Shoot mass and vegetative cover for all five sites. Root mass analysis was done on three Piedmont sites. All the analysis was done using Statistical Analysis System (SAS) software (SAS version 9.1, SAS Institute, Cary, NC). Analysis of Variance (ANOVA) using the PROC GLM procedure was performed on all data. In all sites, the levels of main plots (tillage) arranged in a randomized complete block design (RCBD). All measured dependent variables at Sandhills and Piedmont 1 were analyzed as a split-split-plot design. For Mountain and Piedmont 2, measured dependent variables were analyzed as a split-plot design except for BD and IR data which were analyzed as a split-split-plot design. At piedmont 3, all measured dependent variables were analyzed as a RCBD except for BD and IR which were analyzed as a split-plot design. The defined error terms for each level of analyzing were: main plots x replication as error term for analyzing the effect of main plot, sub-plot x replication (main plot) as error term for analyzing the effect of sub-plot, and sub-sub-plot x replication (main plot x sub-plot) as error term for analyzing the effect of sub-sub-plot. When treatment effects were found significant with F test, means were separated by the least significant difference (LSD) test at P=0.05. When there was no significant effect for any sub-treatments, their data were combined with the main treatment to demonstrate in the table.

Results and Discussion

Soil Compaction

BD after mechanical compaction averaged almost 1.5, 1.9, and 1.5 g cm^{-3} in the upper 15 cm for the all three Piedmont sites, the Sandhills, and Mountain sites, respectively. These values are comparable to those of recently developed sites, as well as other studies on the effect of construction activities on finer textured soils (Alberty et al. 1984; McNabb 1994; Yang and Zhang 2011).

Tillage reduced BD compared to compacted treatments at the Sandhills site each time when it was measured (Table 2.4). There was no difference between different depths of tillage; however, BD was not measured below 15 cm (ST depth). The addition of compost and lime had no impact on BD at this site. BD in the compacted treatment did not appear to change during the 27 months of monitoring; however, the tilled soil increased in BD due to the soil settling over time. ST and DT reduced SPR compared to the compacted treatment from surface to 20 and 30 cm depths, respectively, six months after site establishment (Figure 2.1). The addition of compost and lime did not affect SPR.

At the Mountain site, tillage also reduced BD with the exception of the last sampling (30 months after site establishment) (Table 2.5). Over the course of sampling, BD of the tilled areas increased because of soil settling, while that of the compacted areas decreased because of soil loosening due to grass root growth, until all treatments converged at around 1.2 g cm^{-3} after 30 months. There were no differences in BD between the two tillage depths. Traffic, compost, and xPAM did not affect BD. The SPR at the first measured depth (soil surface; 0 cm) resulted in no difference of tilled treatments and compacted, seven months after site establishment (Figure 2.2). However, ST and DT had lower SPR compared to the compacted treatment from 3 to 20 and 30 cm, respectively. Traffic, compost, and xPAM did not affect SPR.

At Piedmont 1, BD was reduced with tillage at all sampling intervals for the 32 months of monitoring, with no difference between tillage depths (Table 2.6). Like the results at the Sandhills site, BD of compacted soil was relatively stable, while it increased in the tilled treatments but only between the first and second sampling dates. Lime application and additional traffic had no effect on BD. ST and DT treatments reduced SPR significantly compared to compacted from the soil surface to 25 and 30 cm depths, respectively, six months after site establishment (Figure 2.3). Adding different rates of lime as well as applying subplots of traffic and no traffic did not affect the SPR.

The Piedmont 2 site only included compacted, DT and DT+compost. Deep tillage reduced BD compared to compacted treatments at all sampling intervals (Table 2.7). Over the course of sampling, BD of the tilled areas increased because of soil settling, while that of the compacted areas decreased because of soil loosening due to grass root growth. The addition of compost further reduced BD. Adding mower traffic did not affect BD. SPR measurement at 27 months after site establishment showed that DT and DT+compost reduced SPR significantly compared to compacted treatments all the way through profile to the depth of 30 cm, except for soil surface where SPR in DT was not different from the compacted treatment (Figure 2.4). No differences were evident as the result of mower traffic.

The Piedmont 3 site was the only site that consisted of fill material. Similar to other sites, tillage reduced BD at all sampling intervals up to 12 months (Table 2.8), with no clear pattern of increase or decrease over time. Neither the addition of the xPAM nor the gypsum had any effect on BD. However, adding compost to DT reduced BD for all but the last interval. Twelve months after site establishment, SPR measurements showed no difference between any treatments to the measured depth (20 cm) due to large variability (Figure 2.5).

Infiltration Rate

The analysis of variance at Sandhills showed that tillage treatments (main plots) had greater IR ($P \leq 0.01$) compared to compacted (Appendix A). The depth of tillage did not affect the measured IR at each time intervals (Table 2.9). Infiltration was almost three times greater for the tilled treatments compared to compacted at the last time interval, 27 months after site establishment (Table 2.9) and were 34.0 and 33.9 cm h^{-1} for ST and DT, respectively. However, the addition of amendments ($P=0.48$) and different times ($P=0.12$) did not affect the measured IR.

The analysis of variance at Mountain showed that tillage increased IR compared to compacted in all time intervals that it was measured (Appendix A). Infiltration was almost three times greater for the tilled treatments compared to compacted at the last time interval, 30 months after site establishment (Table 2.10) and were 23.7 and 24.0 cm h^{-1} for ST and DT, respectively. The depth of tillage did not affect the measured IR. Applying compost or xPAM did not affect IR ($P=0.27$). There was a significant time effect ($P \leq 0.01$) on IR at this site; IR in the tilled treatments were greater at two months after site establishment compared to the other time intervals that IR was measured. The probable reason for initial rapid surface infiltration conditions in the tilled treatments (38.4 and 43.0 cm h^{-1} for ST and DT, respectively), could be explained by an almost 40% lower BD in the tilled treatments than in compacted (Table 2.5) while this percentage decreased over time because BD of the tilled areas increased because of soil settling, while that of the compacted areas decreased because of soil loosening due to grass root growth, until all treatments converged at around 1.2 g cm^{-3} after 30 months. The effect of additional traffic was measured for the last time interval, 30 months after site establishment (data not shown). The results showed no difference between using mower (as additional traffic) or weed eat to cut the grass.

The analysis of variance at Piedmont 1 showed that tillage treatments (main plots) had greater IR ($P \leq 0.05$) compared to compacted (Appendix A). The depth of tillage did not affect the measured IR at each time intervals (Table 2.11). Infiltration was almost four times greater for the tilled treatments compared to compacted at the last time interval, 32 months after site establishment (Table 2.11) and were 22.1 and 23.0 cm h^{-1} for ST and DT, respectively. The addition of amendments ($P=0.23$) and different times ($P=0.051$) did not affect the measured IR. The effect of additional traffic was measured for the last time interval, 32 months after site establishment (data not shown). The results showed no difference between using mower (as additional traffic) or weed eat to cut the grass ($P=0.08$).

The analysis of variance at Piedmont 2 showed that tillage treatments (main plots) had greater IR ($P \leq 0.01$) compared to compacted (Appendix A). Infiltration (average IR of traffic and no traffic) was around four times greater in DT compared to compacted, 26 months after site establishment (Table 2.12). Compost appeared to improve infiltration compared to DT alone, but this was only statistically significant at the measurement made 13 months after establishment (Table 2.12). The sub-treatments of no traffic and traffic affect the measured IR ($P=0.002$) for DT for the last two measurements; 19 and 26 months after site establishment. At these times, IR was significantly greater in no traffic (29.8 cm h^{-1} for 19th month and 29.4 cm h^{-1} for 26th month) compared to traffic (12.4 cm h^{-1} for 19th month and 10.8 cm h^{-1} for 26th month). There was no time effect (P=0.23) on IR measurements over time in this site.

The analysis of variance at Piedmont 3 showed that tillage treatments (main plots) had greater IR (P≤0.04) compared to compacted (Appendix A). Infiltration at Piedmont 3 was more than three times greater in DT compared to compacted, 12 months after site establishment (Table 2.13). IR in DT with amendments was not different from either compacted or DT alone except at 12 months after site establishment, when IR in DT+xPAM and DT+compost was greater (>2 times) than DT alone. Although DT+gypsum was not different from either DT alone, DT+xPAM or DT+compost, there was one replication of it that the amount of IR was much less than other replications, it caused higher CV compared to the other treatments. After eight months, IR in compacted increased substantially, resulting in no differences among the treatments (Table 2.13). There was a significant time effect (P≤0.01) on IR at this site; IR in the tilled+Amendment treatments were greater at the last time interval, 12 months after site establishment, compared to the other time intervals that IR was measured. This shows that amendments of compost, gypsum and xPAM started having effect on IR before 12 months.

IR measurements from all sites in most of the times that it was measured, showed significantly greater infiltration on tilled plots compared to the compacted. The compacted treatment of Sandhill, Mountain, Piedmont 1, 2, and 3 have an average IR of 6.7, 4.1, 3.8, 4.4, and 3.8 cm h^{-1}, respectively which was comparable with the results of the study by Yang and Zhang (2011); their survey on IR measurements on many developed areas showed that IR was less than 6.3 cm h^{-1}. The average IR on tilled treatments of Sandhill, Mountain, Piedmont 1, 2, and 3 was 31.6, 27.15, 19.8, 23.8 and 14.6 cm h^{-1} respectively which was higher than the highest IR rates found on 65 to 70 year old home lawns (10.0 cm h^{-1}) by Hamilton and Waddington (1999). Also Lipiec (2006) showed that tillage successfully increased IR in agricultural setting by 61%. In our study, IR of the tillage treatment were maintained at >2 times that of compacted soil over the monitoring period at almost all sites.

Different amendments did not seem to have effect on IR except at Piedmont 3, which addition of compost and xPAM showed greater IR compared to DT alone, 12 months after site establishment.

Plant Growth

Shoot mass and vegetative cover

At the Sandhills site, four months after site establishment (November), grass growth was relatively poor, around 10 times less than the other sites, and no significant differences in shoot mass were found among the treatments (Table 2.14). The addition of compost did not have a significant effect on shoot mass. Also, applying lime did not significantly improve shoot mass (data not shown), probably due to the fact that soil pH was 6 resulting in a low lime addition (Table 2.1). Vegetative cover measurement, 10 months after site establishment (May), showed that surface-applied compost on compacted significantly decreased vegetative cover compared to compacted treatment alone and had lowest vegetative cover amongst all the treatments. Surface-application of compost had negative effects on grass germination possibly because organic material becomes hydrophobic and slow to saturate when it becomes dry (Faucette et al. 2004). Compost incorporation on ST and DT did not affect vegetative cover compared to ST and DT alone, respectively.

At the Mountain site, eight months after site establishment (March), no significant differences in shoot mass were found among the treatments (Table 2.15). The addition of compost or xPAM did not have a significant effect on shoot mass (data not shown). In contrast with Sandhills, surface-applied compost on compacted significantly increased vegetative cover compared to compacted alone (Table 2.15). The reason may be explained by the wetter and cooler climate at this site preventing compost from drying and reducing seed germination. Adding traffic did not have any effect.

At Piedmont 1, the results of both shoot mass and vegetative cover, five months after site establishment (June), showed that tillage significantly improved the above-ground grass growth (Table 2.16). The shoot mass for the tilled treatments was almost two times greater than for compacted. Similarly, vegetative covers were 42% on compacted compared to 62% and 56% for ST and DT, respectively. The addition of lime did not affect either shoot mass or vegetative cover (data not shown). Also, traffic had no effect on the above-ground grass growth.

At Piedmont 2, tillage alone did not improve the above-ground grass growth (shoot mass and vegetative cover) (Table 2.17), but the combination of tillage and compost improved the above-ground grass growth compared to both compacted and DT, 27 months after site establishment (July). Traffic did not have significant effect on either shoot mass or vegetative cover.

At Piedmont 3, neither measurement of shoot mass nor vegetative cover indicated a positive effect of tillage with or without the three amendments of compost, xPAM, and gypsum, eight months after site establishment (May) (Table 2.18).

There was not a strong correlation between shoot mass and vegetative cover at Mountain and Piedmont 3. The reason might be the existence of white clover instead of planted grass in some plots at these two sites, which created more vegetative cover and less shoot mass compared to the planted grass.

Root density

At Piedmont 1, at the depth of 0 to 15 cm, the root density was greater in DT compared to compacted but not for ST, five months after site establishment (Table 2.19). At the 15 to 30 cm depths, ST and DT both increased root density compared to the compacted treatment. Adding lime and traffic at this site did not have any effect on root density.

At Piedmont 2, at the depth of 0 to 15 cm, tillage did not show positive effect on root density, 26 months after site establishment (Table 2.20). However, adding compost increased root density compared to compacted at the 15 to 30 cm depth. Mower traffic did not affect root density in either depth.

At Piedmont 3, DT treatments had lower root density than compacted, eight months after site establishment (Table 2.21). In the surface layer of DT, gypsum improved root density relative to DT alone and DT+xPAM. xPAM reduced root density relative to gypsum in DT. Twelve months after site establishment, compost had lower root density in surface layer than compacted, DT, and DT+gypsum. Treatments were not different in the lower layers.

Summary and Conclusions

The overall purpose of this study was to determine if different combinations of tillage and amendments were effective at increasing IR in compacted soils, and if the effects lasted for more than one season. Tillage greatly increased IR and the effect remained after almost three years for the site with the longest monitoring period. There was a decline in IR at tilled treatments at the Mountain site from 2 to 3 months after site establishment because of soil settling at tilled treatments, but not at the other cut sites, although BD tended to increase at all sites. Amendments (compost, gypsum, lime and xPAM) usually had no effect on IR, except at Piedmont 3, where the addition of compost and xPAM showed greater IR compared to DT alone, 12 months after site establishment.

Initial IR for compacted were usually less than 1 cm h^{-1} but numerically improved over several years to around 10 cm h^{-1}, as adjusted by correction factors suggested in the CSI manual. This improvement was significant only at one of the five sites. We attribute this primarily to the effects of the vegetation as the roots slowly penetrated deeper over time. Previous studies have found relatively high IR in lawns that have been established for many years (Hamilton and Waddington 1999), but there have been none that indicated how fast this might be achieved. The tilled soils had IR of 20 to 35 cm h^{-1} (adjusted by the correction factor) at the end of at least two years. Because this far exceeds expected rainfall events in

North Carolina, with generally 3 to 6 cm h^{-1} for 2 to 10 year recurrence storms, the results suggest that treated areas may be able to accept runoff from impervious areas.

In order to develop tools for the design community based on this research, additional work will be necessary. For instance, the data can be used to model longer time periods with different conditions. In addition, many variables remain to be explored, such as tillage equipment and methods, amendment rates and types, and alternative vegetation types. However, this study demonstrated that the proposed tillage and vegetation system was highly successful in improving IR in a wide variety of soil and climates in North Carolina.

Tables and Figures

Table 2.1 Site, establishment timing and soil description at the five sites used in this study.

Site	Establishment	Surface soil characteristics			
		Sand (%)	Silt (%)	Clay (%)	pH
Sandhills (cut)	August 2011/ Jackson Springs, NC	92	6	2	6
Mountain (cut)	August 2011/ Mills River, NC	48	22	30	6
Piedmont 1 (cut)	February 2011/ Raleigh, NC	48	12	40	5.8
Piedmont 2 (cut)	April 2012/ Raleigh, NC	48	12	40	5.8
Piedmont 3 (fill)	October 2013/ Raleigh, NC	44	24	32	6.7

Table 2.2 Treatments for each site

Site	Main tillage treatments	Amendments	Sub-treatments
Sandhills (cut)	Compacted Shallow till Deep till	• Compost (5 cm depth) • Lime (0 and 1500 kg ha^{-1})	
Mountain (cut)	Compacted Shallow till Deep till	• Compost (5 cm depth) • Granular xPAM (320 kg ha^{-1})	Traffic No traffic
Piedmont 1 (cut)	Compacted Shallow till Deep till	• Lime (0 and 1250 kg ha^{-1})	Traffic No traffic
Piedmont 2 (cut)	Compacted Deep till	• Compost (5 cm depth)	Traffic No traffic
Piedmont 3 (fill)	Compacted Deep till	• Compost (5 cm depth) • xPAM (672 kg ha^{-1}) • Gypsum (11.2 Mg ha^{-1})	

Table 2.3 Seed type, rate and fertilizer applied for each site.

Site	Seed applied and rate (kg ha^{-1})	Fertilizer applied (kg ha^{-1})
Sandhills (cut)	• Tall fescue (300) • Bermudagrass (65)	• N=73.2 • K=73.2
Mountain (cut)	• Tall fescue (290)	• N=48.8
Piedmont 1 (cut)	• Hard fescue (84.0) • Kentucky bluegrass (22.4) • Rye grain (28.0)	• N=48.8 • P=97.6 • K=97.6
Piedmont 2 (cut)	• Tall fescue (73.2) • Bermudagrass (29.3) • Centipedegrass (9.8)	• N=48.8 • P=97.6 • K=97.6
Piedmont 3 (fill)	• Tall fescue (73.2) • Bermudagrass (29.3) • Centipedegrass (9.8)	• N=48.8 • P=34.2

Table 2.4 Bulk density over time at Sandhills.

Treatment	BD over time (months after site establishment)			
	1	6	23	27
	-------------------- g cm^{-3} --------------------			
Compacted	1.89a[a]	1.76a[a]	1.89a[a]	1.81a[a]
Shallow till	1.12b[c]	1.45b[b]	1.76b[a]	1.63b[a]
Deep till	1.11b[c]	1.37b[b]	1.74b[a]	1.68b[a]

Note: Means followed by the same letter within a column are not different (p=0.05). Superscript letters signify differences within the row (p=0.05).

Table 2.5 Bulk density over time at Mountain.

Treatment	BD over time (months after site establishment)			
	2	3	23	30
	-------------------- g cm^{-3} --------------------			
Compacted	1.52a[a]	1.38a[a]	1.44a[a]	1.22a[b]
Shallow till	0.92b[b]	1.15b[a]	1.21b[a]	1.22a[a]
Deep till	0.84b[b]	1.05b[ab]	1.16b[a]	1.20a[a]

Note: Means followed by the same letter within a column are not different (p=0.05). Superscript letters signify differences within the row (p=0.05).

Table 2.6 Bulk density over time at Piedmont 1.

Treatment	BD over time (months after site establishment)			
	1	5	29	32
	------------------- g cm^{-3} -------------------			
Compacted	1.48a^{a}	1.49a^{a}	1.44a^{a}	1.52a^{a}
Shallow till	1.11b^{b}	1.35b^{a}	1.28b^{a}	1.28b^{a}
Deep till	1.12b^{b}	1.25b^{a}	1.28b^{a}	1.23b^{a}

Note: Means followed by the same letter within a column are not different (p=0.05). Superscript letters signify differences within the row (p=0.05).

Table 2.7 Bulk density over time at Piedmont 2.

Treatment	BD over time (months after site establishment)			
	7	13	19	26
	------------------- g cm^{-3} -------------------			
Compacted	1.48a^{a}	1.34a^{ab}	1.48a^{a}	1.29a^{b}
Deep till	1.02b^{b}	1.21b^{a}	1.28b^{a}	1.09b^{b}
Deep till+compost	0.66c^{a}	0.66c^{a}	0.76c^{a}	0.78c^{a}

Note: Means followed by the same letter within a column are not different (p=0.05). Superscript letters signify differences within the row (p=0.05).

Table 2.8 Bulk density over time at Piedmont 3.

Treatment	BD over time (months after site establishment)				
	1	3	6	8	12
	-------------------- g cm^{-3} --------------------				
Compacted	1.55a	1.92a	1.70a	1.58a	1.64a
Deep till	1.29b	1.38b	1.43b	1.32b	1.43b
Deep till+compost	1.00c	0.67c	1.15c	1.05c	1.31b
Deep till+xPAM	1.25b	1.31b	1.35b	1.29b	1.24b
Deep till+gypsum	1.28b	1.30b	1.37b	1.30b	1.32b

Note: Means followed by the same letter within a column are not different (p=0.05).
Superscript letters signify differences within the row (p=0.05).

Table 2.9 Infiltration rates over time at Sandhills.

Treatment	IR over time (months after site establishment)				
	1	6	18	23	27
	--------------------cm h^{-1}--------------------				
Compacted	0.3b	2.9b	12.4b	7.1b	11.0b
Shallow till	36.1a	33.8a	31.2a	24.2a	34.0a
Deep till	23.1a	38.5a	34.3a	26.7a	33.9a

Note: Means followed by the same letter within a column are not different (p=0.05).

Table 2.10 Infiltration rates over time at Mountain.

Treatment	IR over time (months after site establishment)			
	2	3	23	30
	--------------------cm h^{-1}--------------------			
Compacted	0.5b[b]	0.6b[b]	7.2b[a]	8.2b[a]
Shallow till	38.4a[a]	23.8a[b]	19.2a[b]	23.7a[b]
Deep till	43.0a[a]	25.6a[b]	19.5a[b]	24.0a[b]

Note: Means followed by the same letter within a column are not different (p=0.05).
Superscript letters signify differences within the row (p=0.05).

Table 2.11 Infiltration rates over time at Piedmont 1.

Treatment	IR over time (months after site establishment)			
	5	16	28	32
	--------------------cm h^{-1}--------------------			
Compacted	3.9b	1.5b	3.0b	6.7b
Shallow till	20.3a	21.6a	11.5a	22.1a
Deep till	21.8a	20.6a	17.1a	23.0a

Note: Means followed by the same letter within a column are not different (p=0.05).

Table 2.12 Infiltration rates over time at Piedmont 2.

Treatment	IR over time (months after site establishment)			
	7	13	19	26
	--------------------cm h^{-1}--------------------			
Compacted / No traffic	0.6c	2.1b	6.8b	2.8b
Compacted / Traffic	1.1c	4.9b	10.7b	6.0b
Deep till / No traffic	26.2ab	12.5b	29.8a	29.4a
Deep till / Traffic	13.3b	4.3b	12.4b	10.8b
Deep till+compost / No traffic	36.6a	31.1ab	31.2a	30.7a
Deep till+compost / Traffic	29.9ab	31.8a	26.1ab	24.3ab

Note: Means followed by the same letter within a column are not different (p=0.05).

Table 2.13 Infiltration rates over time at Piedmont 3.

Treatment	IR over time (months after site establishment)		
	3	8	12
	--------------------cm h^{-1}--------------------		
Compacted	0.8b^{a}	7.5a^{a}	3.1c^{a}
Deep till	14.2a^{a}	9.4a^{a}	14.5b^{a}
Deep till+compost	5.5ab^{b}	11.6a^{b}	30.9a^{a}
Deep till+xPAM	6.7ab^{b}	10.8a^{b}	31.1a^{a}
Deep till+gypsum	6.5ab^{b}	7.4a^{b}	26.6ab^{a}

Note: Means followed by the same letter within a column are not different (p=0.05).
Superscript letters signify differences within the row (p=0.05).

Table 2.14 Dry shoot mass and vegetative cover at Sandhills. (Four and 10 months after site establishment, respectively).

Treatment	Shoot mass (kg ha^{-1})	Vegetative cover (%)
Compacted	147a	62b
Compacted+compost	121a	46c
Shallow till	181a	63b
Shallow till+compost	231a	74ab
Deep till	153a	72ab
Deep till+compost	105a	80a

Note: Means followed by the same letter within a column are not different (p=0.05).

Table 2.15 Dry shoot mass and vegetative cover at Mountain. (Eight months after site establishment).

Treatment	Shoot mass (kg ha^{-1})	Vegetative cover (%)
Compacted	997a	73b
Compacted+compost	1,686a	88a
Shallow till	1,426a	81a
Shallow till+compost	1,167a	82a
Deep till	1,648a	80a
Deep till+compost	1,897a	82a

Note: Means followed by the same letter within a column are not different (p=0.05).

Table 2.16 Dry shoot mass and vegetative cover at Piedmont 1.
(Five months after site establishment).

Treatment	Shoot mass (kg ha^{-1})	Vegetative cover (%)
Compacted	946b	42b
Shallow till	1,597a	62a
Deep till	1,566a	56a

Note: Means followed by the same letter within a column are not different (p=0.05).

Table 2.17 Dry shoot mass and vegetative cover at Piedmont 2.
(Twenty seven months after site establishment).

Treatment	Shoot mass (kg ha^{-1})	Vegetative cover (%)
Compacted / No traffic	1,311b	68b
Compacted / Traffic	1,588b	52b
Deep till / No traffic	784b	47b
Deep till / Traffic	726b	62b
Deep till+compost / No traffic	5,056a	100a
Deep till+compost/ Traffic	4,761a	86ab

Note: Means followed by the same letter within a column are not different (p=0.05).

Table 2.18 Dry shoot mass and vegetative cover at Piedmont 3. (Eight months after site establishment).

Treatment	Shoot mass (kg ha^{-1})	Vegetative cover (%)
Compacted	795a	31a
Deep till	962a	43a
Deep till+compost	812a	45a
Deep till+xPAM	822a	50a
Deep till+gypsum	836a	52a

Note: Means followed by the same letter within a column are not different (p=0.05).

Table 2.19 Root density corresponding to Piedmont 1. (Five months after site establishment).

Treatment	Root density at two depths (cm)	
	0-15	15-30
	--------------------kg m^{-3}--------------------	
Compacted	0.50b	0.02b
Compacted+lime	0.37b	0.01b
Shallow till	0.62ab	0.12a
Shallow till+lime	0.50b	0.25a
Deep till	0.87a	0.25a
Deep till+lime	1.12a	0.25a

Note: Means followed by the same letter within a column are not different (p=0.05).

Table 2.20 Root density corresponding to Piedmont 2.
(26 months after site establishment).

Treatment	Root density at two depths (cm)	
	0-15	15-30
	--------------------kg m^{-3}--------------------	
Compacted	1.14a	0.15b
Deep till	1.05a	0.17ab
Deep till+compost	1.28a	0.27a

Note: Means followed by the same letter within a column are not different (p=0.05).

Table 2.21 Root density corresponding to Piedmont 3.
(Eight and 12 months after site establishment).

Treatment	Root density at two different times after site establishment (month)					
	8			12		
	Depth (cm)					
	0-7.5	7.5-15	15-23	0-7.5	7.5-15	15-23
	--------------------kg m^{-3}--------------------					
Compacted	1.84a	0.75ab	0.72a	1.63a	0.51a	0.85a
Deep till	0.60c	0.92ab	0.46ab	2.12a	0.91a	1.01a
Deep till+compost	0.83bc	0.46ab	0.43ab	0.56b	0.45a	0.40a
Deep till+xPAM	0.52c	0.40b	0.29b	1.33ab	0.48a	0.58a
Deep till+gypsum	1.50ab	1.21a	0.83a	1.82a	0.84a	0.56a

Note: Means followed by the same letter within a column are not different (p=0.05).

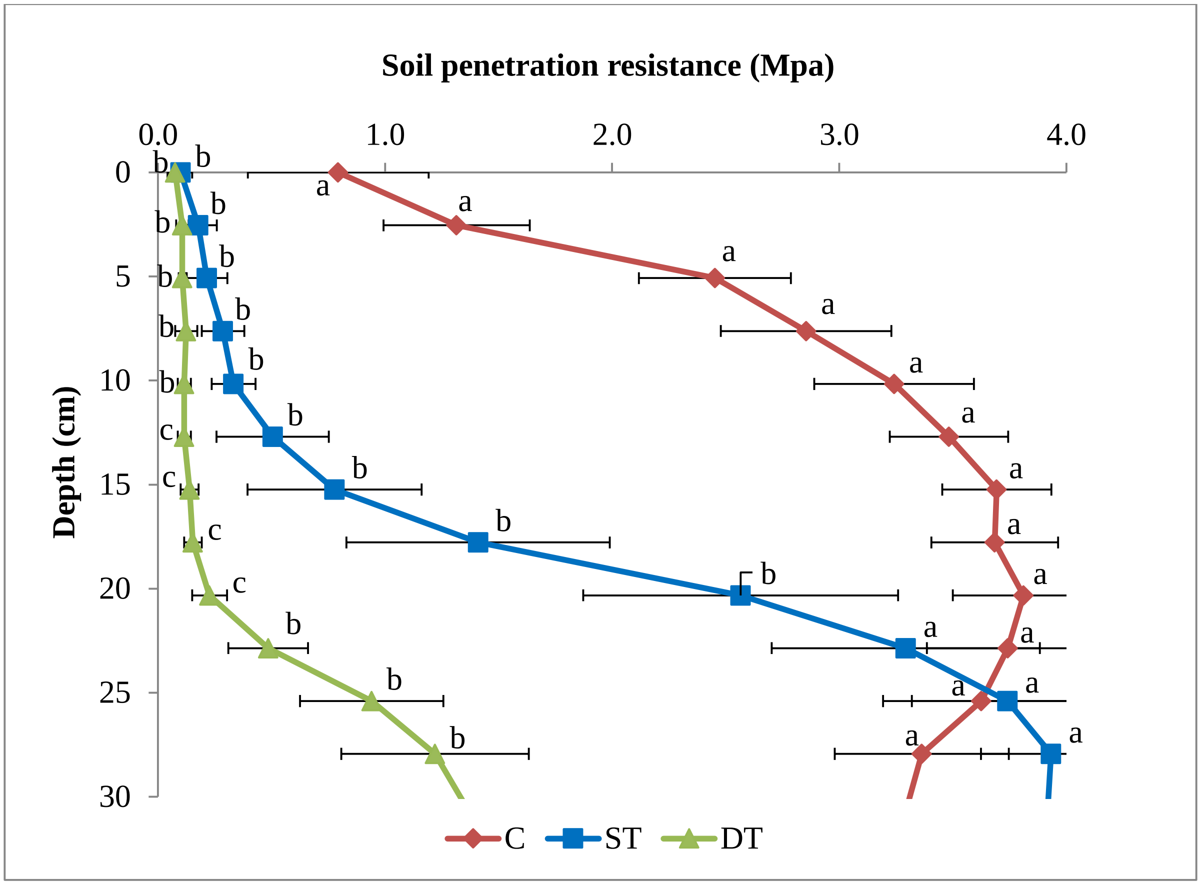

Figure 2.1 Soil penetration resistance versus depth at Sandhills
(Six months after site establishment). C, ST, and DT stand for compacted, shallow till, and deep till treatments, respectively. Error bars demonstrate one standard deviation. Same letter within each depth are not different (p=0.05).

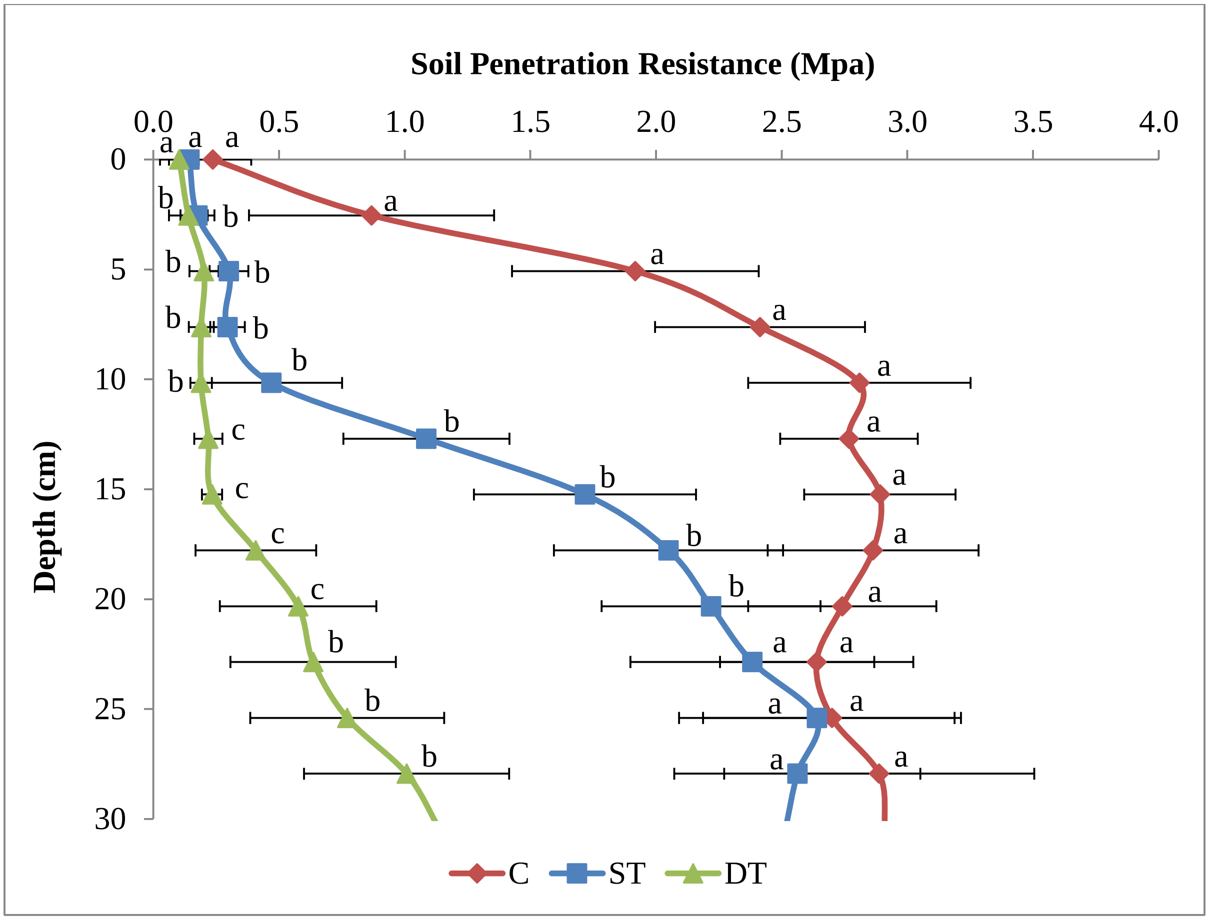

Figure 2.2 Soil penetration resistance versus depth at Mountain (Seven months after site establishment). C, ST, and DT stand for compacted, shallow till, and deep till treatments, respectively. Error bars demonstrate one standard deviation. Same letter within each depth are not different (p=0.05).

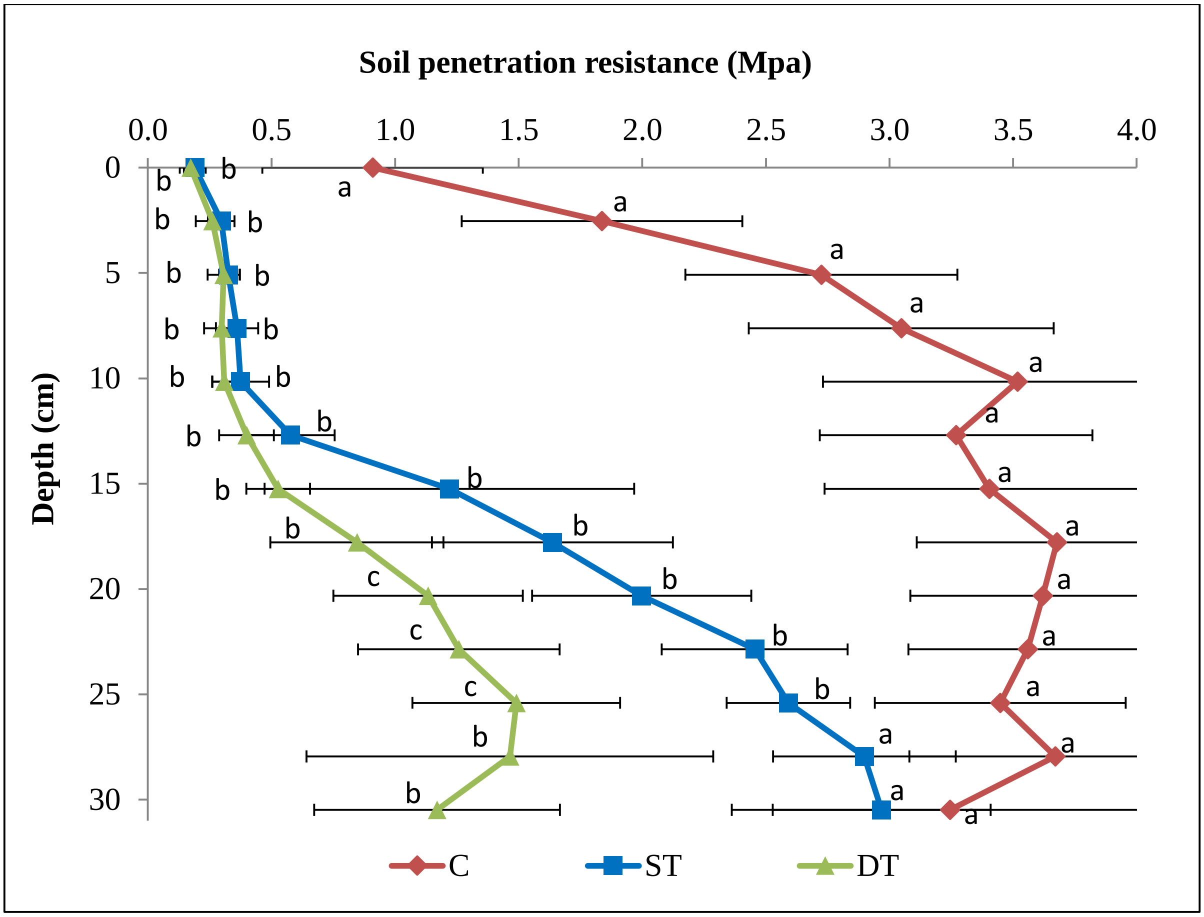

Figure 2.3 Soil penetration resistance versus depth at Piedmont 1 (Six months after site establishment). C, ST, and DT stand for compacted, shallow till, and deep till treatments, respectively. Error bars demonstrate one standard deviation. Same letter within each depth are not different (p=0.05).

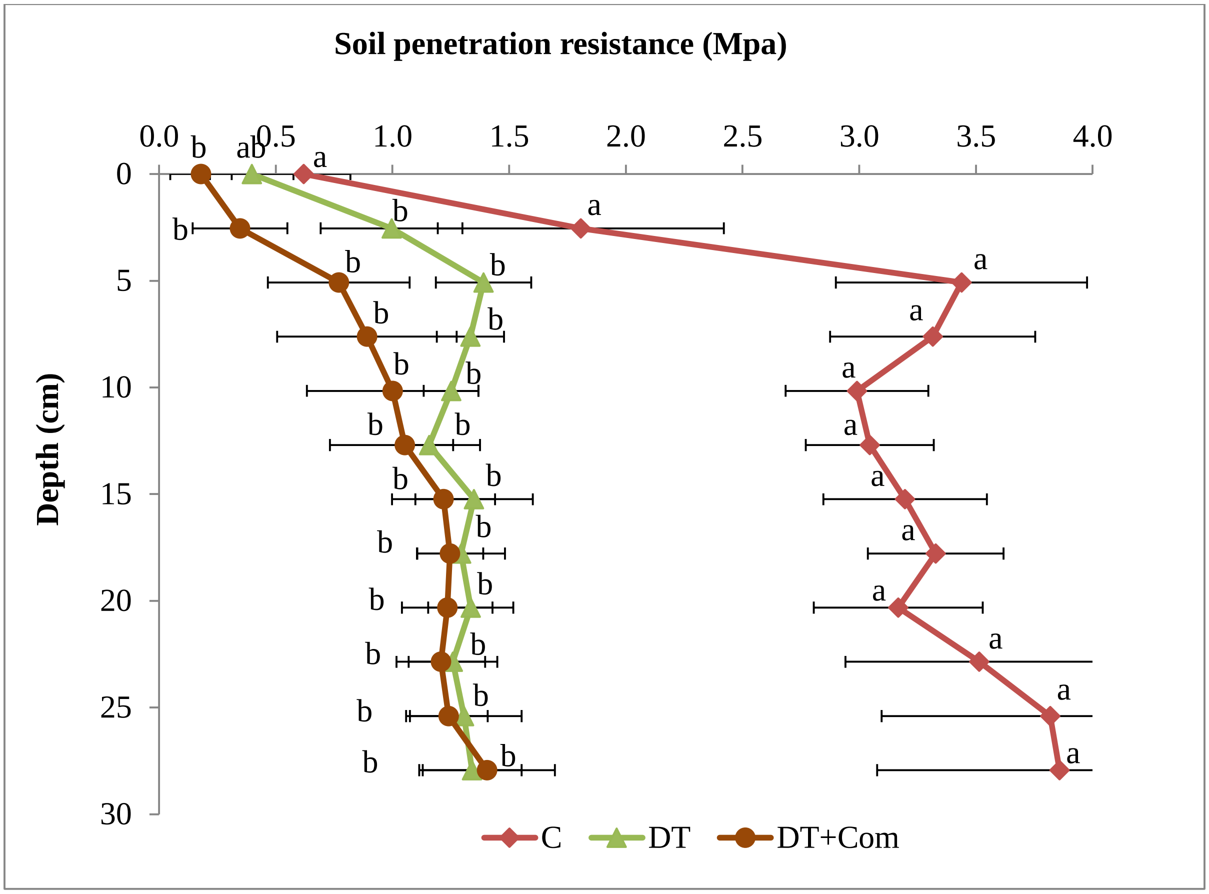

Figure 2.4 Soil penetration resistance versus depth at Piedmont 2 (27 months after site establishment). C, DT and Com stand for compacted, deep till and compost treatments, respectively. Error bars demonstrate one standard deviation. Same letter within each depth are not different (p=0.05).

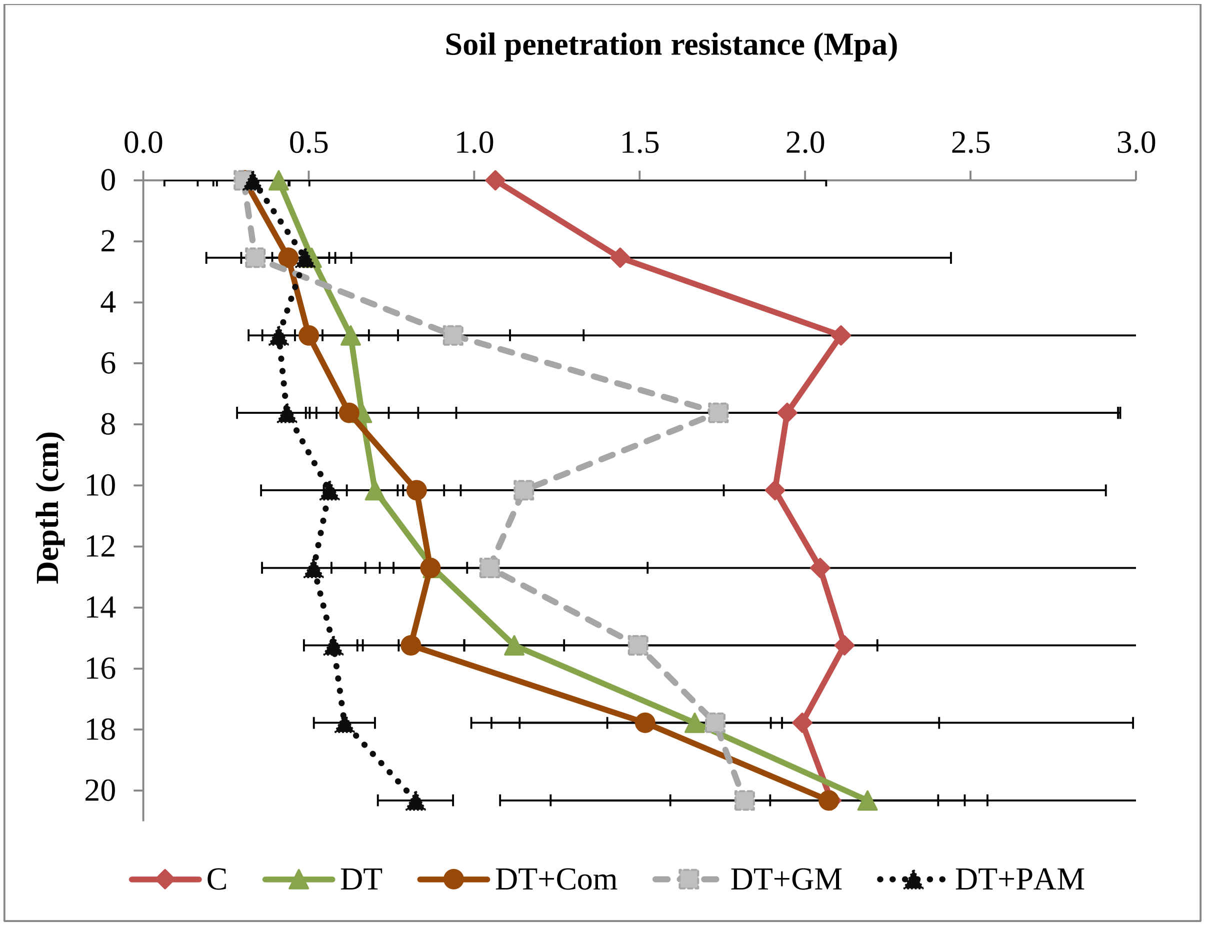

Figure 2.5 Soil penetration resistance versus depth at Piedmont 3 (12 months after site establishment). C, DT, Com, GM and xPAM stand for compacted, deep till, compost, gypsum and cross-linked polyacrylamide treatments, respectively. Error bars demonstrate one standard deviation. Treatments within each depth are not different (p=0.05).

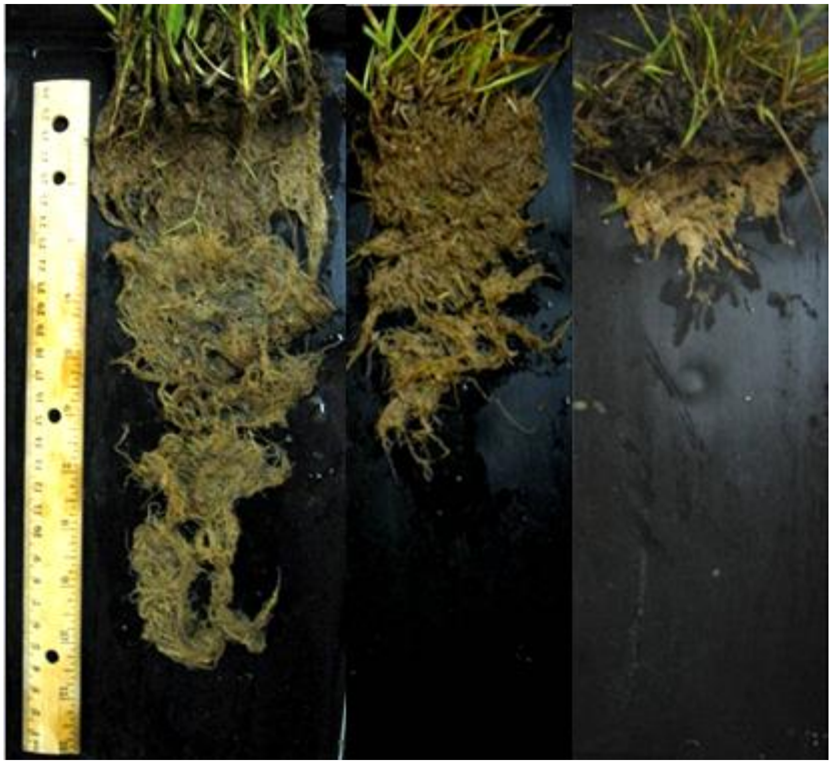

Figure 2.6 Roots sampled at the Sandhills site from Deep till, Shallow till and Control (left to right)

Figure 2.7 Roots sampled at the Mountain site from Deep till, Shallow till and Control (left to right)

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CHAPTER 3 : A GREENHOUSE EXPERIMENT TO SIMULATE VEGETATIVE GROWTH IN POST-CONSTRUCTION SITES

Abstract

During construction activities soil becomes compacted which may hinder soil infiltration and vegetative growth on post-construction site soils. Tillage on post-construction sites could increase soil infiltration and vegetative establishment by loosening the soil, which decreases stormwater runoff and increases overall soil health. A greenhouse study was conducted to determine 1) the effects of tillage on growth of some of the plant species recommended by the NC Department of Transportation, and 2) if any of these species increase saturated hydraulic conductivity (K_s) in either tilled or compacted treatments. The factors were 1) two soil bulk densities (BD) to simulate BD of tilled and compacted soil of post-construction sites, and 2) six single and two mixed species. Shoot mass and vegetative cover were measured during the experiment. Root growth and K_s were measured after the experiment. Compaction level had no effect on shoot and root mass or root length of any individual species in this study. The only effect of BD on vegetation was that root length decreased in the lower BD soil in one of the mixed species. The K_s was over 10 times greater in the low BD soil compared to high BD. Vegetative growth did not affect K_s. These results suggest that

reducing BD through tillage can significantly increase K_s, but the presence of vegetation has no direct benefit during initial growth.

Key words: saturated hydraulic conductivity-soil compaction-tillage-vegetative growth

Introduction

During construction, activities such as grading and heavy equipment traffic make the soil compacted (Batey and McKenzie 2006; Gregory et al. 2006; Olson et al. 2013). This can make vegetative establishment challenging on post-construction sites. Studies showed that compaction reduced root growth (Alberty et al. 1984; Gilman et al. 1987). Plants with shallow roots are more susceptible to drought stress and do not create deep channels for water infiltration (Bartens et al. 2008; Bouma and Dekker 1978; Hino et al. 1987).

Good vegetative establishment plays an important role in controlling runoff volume and sediment loss. Pan and Shangguan (2006) found that soils with vegetative cover of 35%, 45%, 65% and 90% reduced runoff by 14–25% and sediment loss by 81–95% compared to bare soil.

The effects of roots on soil structure and soil infiltration have been summarized in recent reviews by Gregory (2006) and Hinsinger et al. (2009). Detailed studies have shown that the soil adjacent to the root, called the rhizosphere soil, can have different soil infiltration than the bulk soil, which is unaffected by root growth. In comparison with bulk soil, root growth can increase the water release characteristic of the rhizosphere soil (Whalley et al. 2005) as well as its hydraulic conductivity (Hallett et al. 2003; Whalley et al. 2004).

The explanation for these changes to soil hydraulic function in the rhizosphere has been related to changes in soil structure (Whalley et al. 2005) and differences in the contact angle between water and the soil solids surface (Hallett et al. 2003). The effects of the growth of different plants on soil infiltration in the field have been reported by Bodner et al. (2008) and Hu et al. (2009). Both of these accounts show that the effect on water infiltration depends on plant species (Macleod et al. 2007).

Using tillage in post-construction sites (after all construction activities are completed), could increase infiltration rate and vegetative establishment, which decreases stormwater runoff and increases overall soil health (Olson 2013). There are a variety of different species recommended by the North Carolina Department of Transportation (NCDOT) for post-construction sites. Knowing the effect of tillage on these species could help us to choose species which have more impact on controlling runoff and erosion. To investigate tillage influence on species, a greenhouse study was conducted with simulated tillage and compacted treatments in columns. The objectives of this study were to determine 1) the effects of BD on differential growth of species recommended by NCDOT, and 2) if any of these species increased saturated hydraulic conductivity (K_s) in either tilled or compacted treatments.

Materials and Methods

A greenhouse study was conducted from 20 August to 20 November, 2013 (90 days) in a randomized complete block design with three replicates.

Treatments

The factors were: 1) two soil bulk densities (BD) = 1.2 g cm^{-3} (low BD; simulated tillage treatment) and 1.5 g cm^{-3} (high BD; simulated compacted treatment), 2) eight plant species and mixes including three warm-season species: centipedegrass (*Eremochloa ophiuroides*), bermudagrass (*Cynodon dactylon*), bahiagrass (*Paspalum notatum Flugge*); three cool-season species: tall fescue (*Festuca arundinacea*), Kentucky bluegrass (*Poa pratensis*), white clover (*Trifolium repens L.*); and two mixed species: Mix 1 with tall fescue, centipedegrass and bermudagrass, Mix 2 with hard fescue (*Festuca trachyphylla*), Kentucky bluegrass and rye grain (*Secale cereal*). Seed was applied according to recommended rates specified by the NCDOT at the time of planting (Roadside Environmental Unit, Grass Management) (Table 3.1).

Columns

Polyvinyl chloride (PVC) columns (20.3 cm high by 10.2 cm inside diameter purchased from M. A. Industries Inc., Peachtree City, GA) were used as columns in this study. Inside walls of the column were covered with Spinout (American Hydrotech, Inc., Chicago, IL) to prevent roots from growing between soil core and column walls (Figure 3.1). A barbed fitting was installed near the bottom to capture and release water for measuring K_s (Figure 3.2 and Figure 3.3). The bottom 2.5 cm of each column was filled with coarse sand to distribute water flow and for aeration.

Soil

A clay loam subsoil (41% sand, 22% silt, 37% clay; pH 5.4) from a construction site in the Raleigh, NC area was chosen for the study. The soil was air dried, ground, and sieved. A sample was submitted to the North Carolina Department of Agriculture and Consumer Services (NCDA&CS) for analysis and fertilizer and lime recommendations for turfgrasses. Particle size analysis was performed on soil samples using the hydrometer method (Gee and Bauder 1986).

Soil water content at field capacity, which is the upper limit of plant available water, was measured by equilibrating samples in a low pressure chamber system (Cassel and Nielsen 1986). This water content was chosen to ensure that water stress was not a limiting factor in our experiment. The low pressure chambers were equilibrated at 3.3 kPa (0.33 bar) as an estimate of field capacity. The field capacity water content was used as the target water content for watering during the experiment (described below).

Experiment

Columns were filled with soil to 1 cm of the rim for the low BD columns; for the high BD columns the soil was packed with a drop hammer in 2-3 cm layers up to 1 cm of the rim (Figure 3.4). The columns were then carefully transferred to a greenhouse for the plant growth testing. Soil tests resulted in a recommended application of 0.097 kg m^{-2} of 5-10-10 (N-P-K) fertilizer. To simulate a tillage treatment, fertilizer was mixed with the soil and the mixture was returned to the columns in bulk density of 1.2 g cm^{-3}. To simulate compacted treatment, fertilizer was surface-applied to the columns with bulk density of 1.5 g cm^{-3}. Seeds were mixed with the top 1 cm of the soil. Seed viability testing were performed using Tetrazolium method prior to planting (Grabe 1970). Initially water was added to columns to the target water content estimated as field capacity, and then columns were watered approximately every three days, adding only the amount of water that was lost as determined by weighing (Figure 3.5). The average daily maximum and minimum temperatures of the greenhouse during the experiment were 33 and 21 ºC, respectively.

Six additional columns were planted to tall fescue and destructively sampled approximately each 30 days to confirm rooting depth was still above the coarse sand layer at the bottom of columns. Six bare soil columns were prepared and watered for K_s measurement at the end of the experiment.

Shoot Mass and Vegetative Cover

During the experiment, plants were clipped to a height of 5 cm monthly. The clippings were put in an envelope, oven dried at 65 ºC for 48 hours, and then weighed to determine shoot mass. At the end of the experiment, the results of each shoot mass measurement were summed to provide total biomass for the experiment period.

Also, vegetative cover was estimated for all columns by taking photos with a digital camera (model No. TG-320 Olympus Imaging Corp., Tokyo, Japan) at 9, 15 and 26 days after planting from 20 cm above the surface, and analyzed using the geographic information system (GIS) program ArcMap (Esri, Redlands, CA). Images were evaluated for the number of green pixels and the number of non-green pixels to determine vegetative cover. At the end of the experiment, the last measurement of shoot mass was performed in the same way as the monthly clippings.

Saturated Hydraulic Conductivity Measurement

For the K_s measurements, columns were saturated by putting them in buckets with water and letting the water enter from the three holes in the bottom side of each column. After the soil in columns was saturated, columns were moved to the hydraulic conductivity measurement table. Constant head was established and recorded without flow (Figure 3.6). Then a clamp attached to the barbed fitting of bottom of each column was opened and outflow rates were measured for 10 seconds in columns with low BD and 10 minutes in columns with high BD. To calculate K_s, Darcy's equation was used:

$$Ks = \left(\frac{V}{At}\right).\frac{L}{H}$$

where K_s is saturated hydraulic conductivity (m/s), A is soil cross-sectional area (m^2), L is length of soil in core (m), t is time (s), V is volume of outflow (m^3) and H is hydraulic head (m).

Root Measurements

Root measurements were completed after K_s measurements. The columns were cut vertically and the soil cores were removed. The soil cores then were washed to remove the soil from roots under a steady stream of water on a 1.70 mm U.S.A. standard testing sieve (A.S.T.M.E.-11 specification, Fisher Scientific Company) (Figure 3.7). The roots then were put on a paper towel and their vertical length was measured (Appendix C). The roots were cut into 2.5 cm lengths, placed in a paper envelope, and oven dried at a temperature of 65ºC. After 48, hours the samples were removed from the oven and equilibrated for few hours to reach room temperature and then weighed.

Statistical Analysis

SAS Software was used to perform all statistical analyses (SAS version 9.1, SAS Institute, Cary, NC). Analysis of Variance (ANOVA) using the PROC GLM procedure was performed on all data to analyze main effects and was used to separate treatments. Significant differences were measured at α=0.05, unless otherwise noted.

Results and Discussion

Seed Testing

The viability results for seeds were: 98% in centipedegrass, 98% in bermudagrass, 96% in bahiagrass, 76% in tall fescue, 76% in Kentucky bluegrass, 96% in white clover, 18% in hard fescue, and 94% in rye grain.

Shoot Mass

For all species and mixtures, shoot mass was no greater in the low BD soil compared to the compacted soil (Table 3.2). For the cool-season species, shoot mass was greater in tall fescue compared to white clover in both high and low BD. There was no interaction between BD and species. Other studies have found that soil compaction did not have any effect on shoot mass of bermudagrass (Arrieta et al. 2009) and tall fescue (Carrow 1980). However, in a study conducted by Matthieu et al. (2011), shoot mass was reduced by increased compaction in centipedegrass, bermudagrass and tall fescue. Several studies also reported that soil compaction reduced shoot density in Kentucky bluegrass (Carrow 1980; Matthieu et al. 2011; O'Neil and Carrow 1982).

Vegetative Cover

In warm-season species, nine days after planting, the low BD soil had a greater vegetative cover of bermudagrass compared to high BD (Table 3.3). At that time, bermudagrass had the greatest vegetative cover among other species in low BD. Twenty-six days after planting, vegetative cover in bahiagrass was higher in the low BD treatment compared to the compacted treatment. At that sampling, bermudagrass and bahiagrass showed greater vegetative cover relative to centipedegrass in low BD. Among the cool-season species, vegetative cover for tall fescue was greater compared to compacted, nine days after planting (Table 3.3). Carrow (1980) also found the reduction of turf cover of tall fescue as compaction stress increased. In the low BD treatment, tall fescue had the greatest vegetative cover at both 9 and 15 days after planting, but this difference disappeared at 26 days after planting. In mixed species, vegetative cover measurements at 9, 15 and 26 days after planting was not affected by BD for any mixed species (Table 3.3). Also there was no difference between the two mixed species in low BD at any measured times. There was no interaction between BD and species in the vegetative cover results.

Root Growth

For each species in the three groups of warm-, cool-season and mixed species, root mass was not affected by BD (Table 3.2). Also, BD did not have any effect on root length except for Mix1 which the root length was longer in high BD compared to low BD. Other studies also found no effect of compaction on root dry weight of bermudagrass (Arrieta et al. 2009), Kentucky bluegrass (Matthieu et al. 2011; O'Neil and Carrow 1982), and tall fescue (Carrow 1980). In low BD for the group of cool-season species, tall fescue had longer root length compared to white clover. There was no interaction between BD and species in root mass or root length results.

Saturated Hydraulic Conductivity

As expected, K_s was much higher in the low BD soil compared to the high BD soil, but it was not affected by plant species or presence of plants (Table 3.2 and Table 3.4). There was no interaction between BD and species. Also, the correlation between K_s with shoot mass, root mass, and length was weak, further illustrating the lack of effect (Table 3.5). These results showed that the effects of the tillage on K_s was not related to vegetative growth but that it was due to the different soil physical characteristics between low and high BD. Also in a previous study by authors (Mohammadshirazi 2015), initial tillage increased soil infiltration more than 10 times compared to the compacted treatments. In a study conducted by Olsen (2013), results showed that using tillage in post-construction site increased soil infiltration as well as vegetation establishment.

Conclusion

This controlled greenhouse experiment evaluated the effect of compaction level on vegetative growth for three warm-, three cool-season and two mixed species as well as K_s. The compacted soil had BD similar to that measured on construction sites and in previous studies, while the low BD soil (simulated tillage) was similar to that of soils compacted and subsequently tilled. Compaction level had no effect on shoot and root mass or root length of any individual species in this study. The only effect of BD on vegetation was that root length decreased in the lower BD soil in Mix 1. K_s was over 10 times greater in the low BD soil, but vegetative growth did not affect K_s. These results suggest that reducing BD through tillage can significantly increase K_s, but the presence of vegetation has no direct benefit initially. On field sites, however, the cover would prevent erosion and may have benefits to K_s over longer periods of time.

Tables and Figures

Table 3.1 Recommended NCDOT single and mixed species and planting rate.

Single species	**kg ha^{-1}**
Tall fescue	112.0
Bermudagrass	28.0
Centipdedgrass	11.2
Bahiagrass	112.0
Kentucky Bluegrass	44.8
White clover	3.9
Mix 1	
Tall fescue	56.0
Bermudagrass	28.0
Centipdedgrass	11.2
Mix 2	
Hard fescue	84.0
Kentucky bluegrass	22.4
Rye grain	28.0

Table 3.2 Shoot mass, root mass, root length and saturated hydraulic conductivity of all species. Coefficient of variation is shown in parenthesis (the unit is percentage).

	Shoot mass (g column^{-1})		Root mass (g column^{-1})		Root length (cm)		K_s (mm h^{-1})	
	Bulk density (g cm^{-3})							
Warm-season species	**1.2**	**1.5**	**1.2**	**1.5**	**1.2**	**1.5**	**1.2**	**1.5**
Bermudagrass	3.71 (44)	1.02 (91)	1.12 (43)	0.81 (86)	18.6 (40)	19.9 (21)	18.24^{a} (16)	0.51^{b} (43)
Centipedegrass	0.09 (173)	0.16 (133)	2.51 (73)	0.19 (82)	14.6 (59)	14.6 (33)	21.23^{a} (16)	0.53^{b} (173)
Bahiagrass	3.85 (51)	0.15 (96)	3.09 (106)	0.26 (99)	20.1 (5)	19.1 (18)	19.76^{a} (51)	1.14^{b} (50)
P value	***0.24***	***0.15***	***0.75***	***0.09***	***0.5***	***0.3***	***0.76***	***0.34***
Cool-season species								
Tall fescue	3.77a (35)	2.2a (54)	1.8 (31)	1.52 (64)	22.3a (5)	19.1 (20)	29.41^{a} (13)	0.98^{b} (101)
Kentucky bluegrass	1.89ab (88)	1.03ab (75)	1.87 (115)	1.39 (106)	16.2ab (49)	11.7 (67)	22.66^{a} (20)	0.38^{b} (101)
White clover	0.46b (173)	0b -	0.08 (172)	0.03 (67)	7.7b (92)	10.6 (29)	25.08^{a} (26)	0.48^{b} (91)
P value	***0.05***	***0.05***	***0.48***	***0.13***	***0.05***	***0.5***	***0.61***	***0.64***
Mixed species								
Mix1	2.3 (37)	2.62 (27)	1.33 (44)	2.18 (92)	18^{b} (11)	22.7^{a} (9)	47.44^{a} (81)	1.73^{b} (83)
Mix2	5.84 (31)	1.72 (8)	4.51 (57)	4.88 (33)	15 (100)	16.9 (49)	37.29^{a} (55)	0.47^{b} (91)
P value	***0.32***	***0.44***	***0.30***	***0.44***	***0.5***	***0.3***	***0.76***	***0.47***

Note 1: Means followed by the same letter within a column for each group are not statistically different (p=0.05). Superscript letters signify differences between low and high BD in each species (p=0.05).
Note 2: Mix 1 contained of tall fescue, centipedegrass and bermudagrass and Mix 2 contained of hard fescue, Kentucky bluegrass and rye grain.

Table 3.3 Vegetative cover over time for different group.

	Time after planting (day)					
	9		**15**		**26**	
	Bulk density (g cm^{-3})					
	1.2	**1.5**	**1.2**	**1.5**	**1.2**	**1.5**
Warm-season species	**Vegetative cover (%)**					
Bermudagrass	8a^{a}	0^{b}	27	11a	48a	27a
Centipedegrass	0b	0	9	0b	19b	12b
Bahiagrass	1b	0	23	0b	50a^{a}	7b^{b}
P value	***0.007***	**-**	***0.21***	***0.04***	***0.02***	***0.04***
Cool-season species	**Vegetative cover (%)**					
Tall fescue	6a	0	54a	37a	61	36a
Kentucky bluegrass	0b	1	11b	3b	25	17b
White clover	0b	1	9b	8b	23	4b
P value	***0.007***	***0.10***	***0.01***	***0.03***	***0.27***	***0.02***
Mixed species	**Vegetative cover (%)**					
Mix 1	18	0	33	19	55	45
Mix 2	21	0	39	27	66	49
P value	***0.83***	***0.35***	***0.36***	***0.15***	***0.83***	***0.88***

Note 1: Means followed by the same letter within a column for each group are not statistically different (p=0.05). Superscript letters signify differences between low and high BD in each species (p=0.05).
Note 2: Mix 1 contained of tall fescue, centipedegrass and bermudagrass and Mix 2 contained of hard fescue, Kentucky bluegrass and rye grain.

Table 3.4 Saturated hydraulic conductivity of all species with the control (bare soil).

Vegetative species	K_s (mm h^{-1})	
	Bulk density (g cm^{-3})	
	1.2	1.5
Bermudagrass	18.24b	0.51ab
Centipedegrass	24.67ab	0.53ab
Bahiagrass	19.76ab	1.14ab
Tall fescue	29.41ab	0.98ab
Kentucky bluegrass	22.66ab	0.38b
White clover	25.08ab	0.48ab
Mix1	49.05a	1.73a
Mix2	35.18ab	0.47ab
Control	29.03ab	0.75ab

Note 1: Means followed by the same letter within a column for each group are not statistically different (p=0.05).
Note 2: Mix 1 contained of tall fescue, centipedegrass and bermudagrass and Mix 2 contained of hard fescue, Kentucky bluegrass and rye grain.

Table 3.5 Correlation between different measured parameters.

	Shoot mass	Root mass	Root length	K_s
Shoot mass	1	0.40	0.43	0.49
Root mass	-	1	0.37	0.14
Root length	-	-	1	0.11
K_s	-	-	-	1

Figure 3.1 Covering the inside walls of the columns with root inhibitor.

Figure 3.2 Making drainage holes to install barbed fitting.

Figure 3.3 Completed column with barbed fitting for capturing and draining water.

Figure 3.4 Packing soil into column using a drop hammer

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Figure 3.5 Randomized complete blocked design experiment in the greenhouse. The columns were watered to the target weight.

Figure 3.6 Saturated hydraulic conductivity measurement apparatus.

Figure 3.7 Washing soil from roots using a stream of water on a soil sieve.

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APPENDICES

Appendix A. Tables of Analysis of Variance Conducted on Infiltration Rate Data at The Five Sites.

Table A1 Degree of freedom (df), sum of square (SS), Mean square and F value from the analysis of variance conducted on infiltration rate data at Sandhills.

Sources of variation	df	SS	MS	F
Tillage	2	8732.89	4366.45	19.96**
Replication	3	216.77	72.26	0.33
Error A	6	1312.87	218.81	
Amendment (Amend)	4	550.01	137.50	0.90
Tillage x Amend	3	275.52	91.84	0.60
Error B	21	3221.97	153.43	
Month	4	268.82	134.41	2.21
Tillage x Month	4	96.50	24.12	0.40
Amend x Month	6	274.31	45.72	0.75
Tillage x Amend x Month	6	233.55	38.93	0.64
Error C	48	2917.67	60.78	

** indicates significance at $P \leq 0.01$.

Table A2 Degree of freedom (df), sum of square (SS), Mean square and F value from the analysis of variance conducted on infiltration rate data at Mountain.

Sources of variation	df	SS	MS	F
Tillage	2	10111.59	5055.80	43.95**
Replication	3	353.25	117.75	1.02
Error A	6	690.23	115.04	
Amendment (Amend)	2	137.17	68.59	1.43
Tillage x Amend	3	362.60	120.87	2.52
Error B	15	720.14	48.01	
Month	3	2407.82	802.61	10.16**
Tillage x Month	6	2669.59	444.93	5.63**
Amend x Month	6	500.31	83.38	1.06
Tillage x Amend x Month	9	1123.79	124.87	1.58
Error C	57	4502.32	78.99	

** indicates significance at $P \leq 0.01$.

Table A3 Degree of freedom (df), sum of square (SS), Mean square and F value from the analysis of variance conducted on infiltration rate data at Piedmont 1.

Sources of variation	df	SS	MS	F
Tillage	2	6107.37	3053.69	20.83*
Replication	3	243.93	81.31	0.55
Error A	6	879.47	146.58	
Amendment (Amend)	2	217.79	108.89	1.67
Tillage x Amend	2	170.62	85.31	1.31
Error B	12	784.03	65.34	
Month	3	604.89	201.63	2.74
Tillage x Month	6	287.39	47.90	0.65
Amend x Month	6	59.37	9.90	0.13
Tillage x Amend x Month	6	116.74	19.46	0.26
Error C	63	4630.15	73.49	

*indicates significance at $P \leq 0.05$.

Table A4 Degree of freedom (df), sum of square (SS), Mean square and F value from the analysis of variance conducted on infiltration rate data at Piedmont 2.

Sources of variation	df	SS	MS	F
Tillage	2	8000.36	4000.18	107.22**
Replication	2	8.40	4.20	0.11
Error A	4	149.23	37.31	
Mow	1	518.74	518.74	24.58**
Tillage x Mow	2	863.81	431.91	20.47**
Error B	6	126.61	21.10	
Month	3	243.58	81.19	1.50
Tillage x Month	6	720.44	120.07	2.22
Mow x Month	3	90.72	30.24	0.56
Tillage x Mow x Month	6	75.34	12.56	0.23
Error C	36	1951.36	54.20	

** indicates significance at $P \leq 0.01$.

Table A5 Degree of freedom (df), sum of square (SS), Mean square and F value from the analysis of variance conducted on infiltration rate data at Piedmont 3.

Sources of variation	df	SS	MS	F
Tillage	4	1415.72	353.93	3.59*
Replication	3	587.00	195.67	1.99
Error A	12	1182.79	98.57	
Month	2	2736.17	1368.08	22.73**
Tillage x Month	8	1808.53	226.07	3.76*
Error B	30	1805.74	60.19	

*indicates significance at $P \leq 0.05$.
** indicates significance at $P \leq 0.01$.

Appendix B. Pictures Corresponding to the Field Research Activities

Figure B1 Cornell Sprinkle Infiltrometer measurement at the Mountain site. The clear tank is the reservoir, with emitter tubes on the bottom to release droplets onto the surface. Runoff within the ring inserted into the ground (tank sits on top of that) is collected in a beaker in the hole dug next to the test area.

Figure B2 Runoff collection systems at Piedmont 1.

Figure B3 Plot establishment at Piedmont 1. In the foreground is a compacted plot, with straw and jute matting applied after seed, fertilizer, and lime were added. The jute matting was removed once the grass began to grow through it. The trencher was used to create drainage around the plots. The mini-excavator for initial soil breakup and the tractor-mounted rotary tiller are also shown.

Figure B4 Compost and lime being incorporated into the soil at the Sandhills site.

Figure B5 After compaction with a vibratory roller, a backhoe was used for initial loosening, followed by a rotary tiller, at Piedmont 2.

Figure B6 Plots one month after establishment showing the runoff collection system, Piedmont 2.

Figure B7 Bulk density measurement with core sampling in Mountain site.

Figure B8 Compacting the subsoil, Piedmont 3.

Figure B9 Adding fill, Piedmont 3.

Figure B10 Applying treatments and fertilizer, Piedmont 3.

Figure B11 Applying seed and covering plots at Piedmont 3.

Figure B12 Applying hydromulch around plots, Piedmont 3.

Appendix C. Pictures Corresponding to the Roots of Warm-, Cool-Season and Mixed Species in the Greenhouse Experiment

Figure C1 Roots of Bermudagrass in bulk density 1.5 g cm^{-3} in three replications.

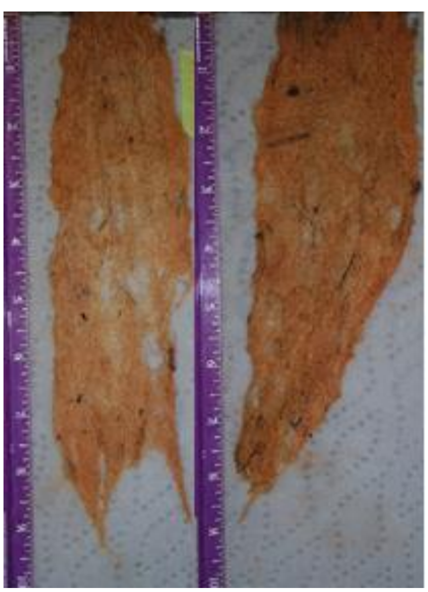

Figure C2 Roots of Bermudagrass in bulk density 1.2 g cm^{-3} in three replications (taking photo for one of the replications was missed).

Figure C3 Roots of centipedegrass in bulk density 1.5 g cm^{-3} in three replications.

Figure C4 Roots of centipedegrass in bulk density 1.2 g cm^{-3} in three replications.

Figure C5 Roots of bahiagrass in bulk density 1.5 g cm^{-3} in three replications.

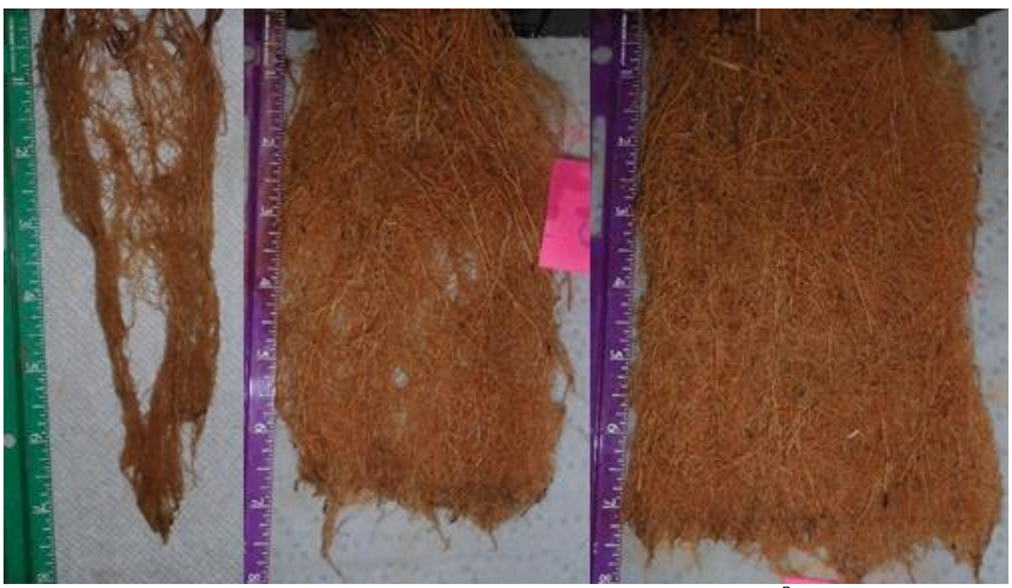

Figure C6 Roots of bahiagrass in bulk density 1.2 g cm^{-3} in three replications.

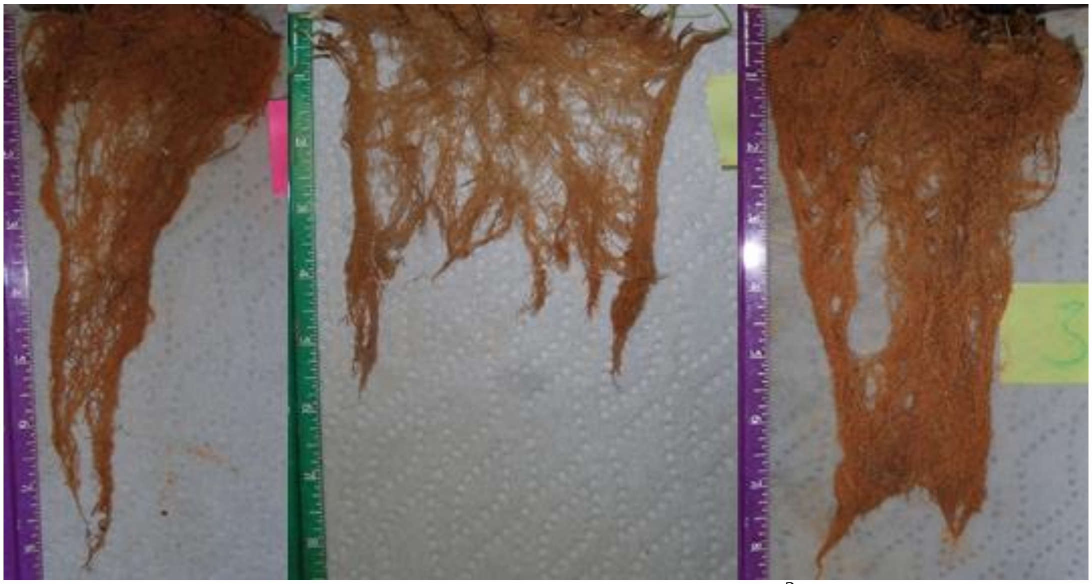

Figure C7 Roots of tall fescue in bulk density 1.5 g cm^{-3} in three replications.

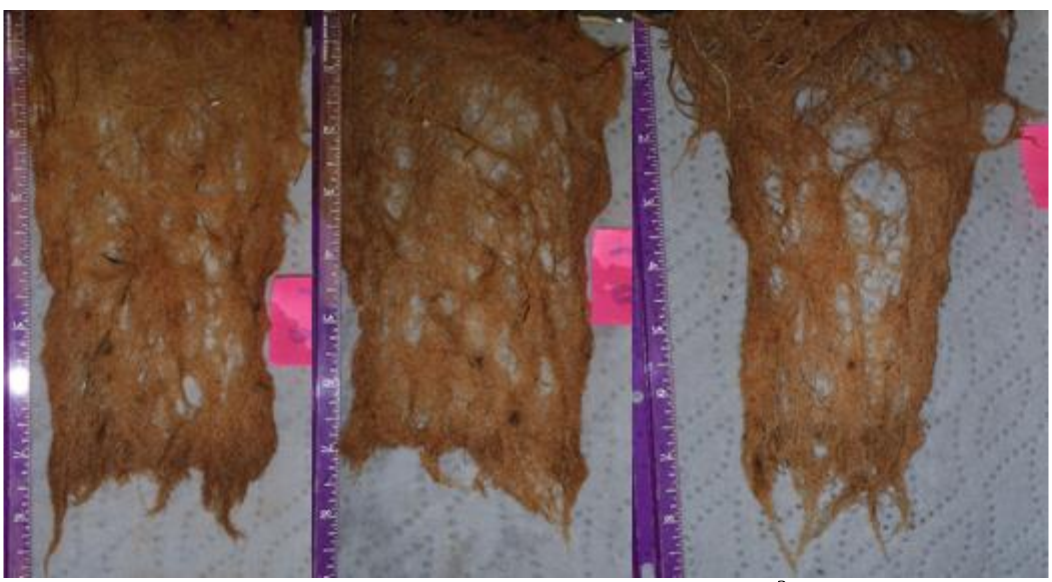

Figure C8 Roots of tall fescue in bulk density 1.2 g cm^{-3} in three replications.

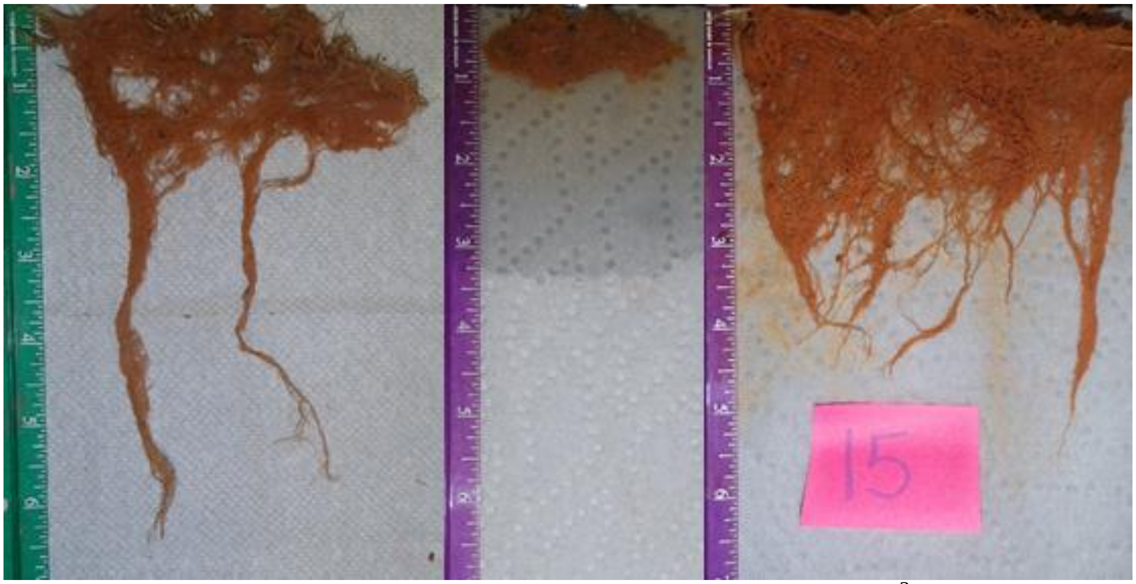

Figure C9 Roots of Kentucky bluegrass in bulk density 1.5 g cm^{-3} in three replications.

Figure C10 Roots of Kentucky bluegrass in bulk density 1.2 g cm^{-3} in three replications.

Figure C11 Roots of white clover in bulk density 1.5 g cm^{-3} in three replications.

Figure C12 Roots of white clover in bulk density 1.2 g cm^{-3} in three replications (There was not any root in one replication).

Figure C13 Roots of Mix 1 in bulk density 1.5 g cm^{-3} in three replications (taking photo for one of the replications was missed).

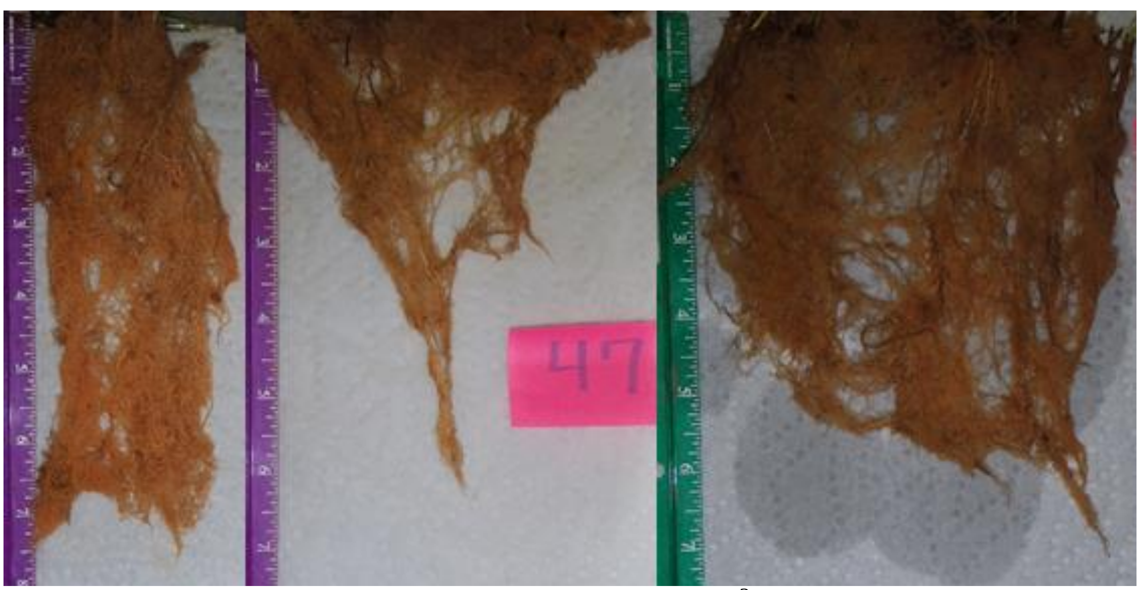

Figure C14 Roots of Mix 1 in bulk density 1.2 g cm^{-3} in three replications.

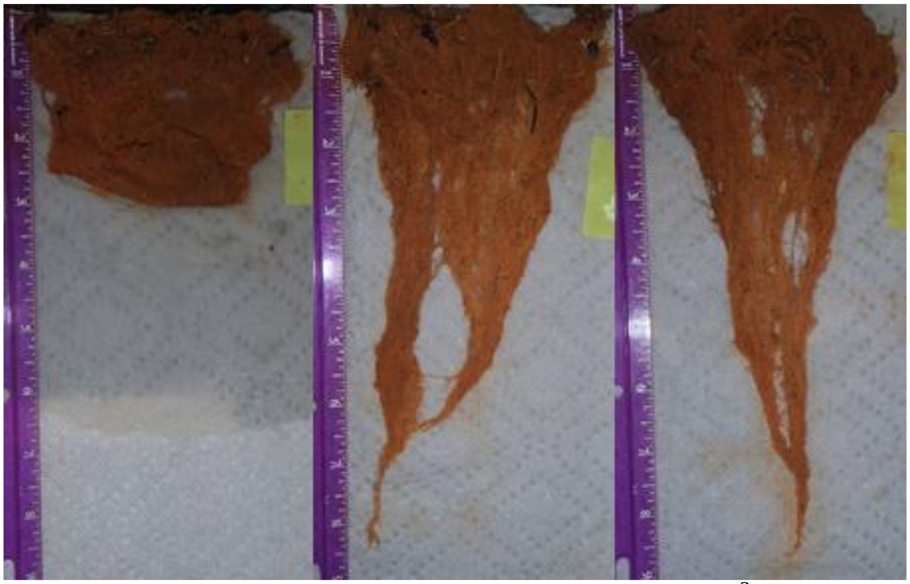

Figure C15 Roots of Mix 2 in bulk density 1.5 g cm^{-3} in three replications**.**

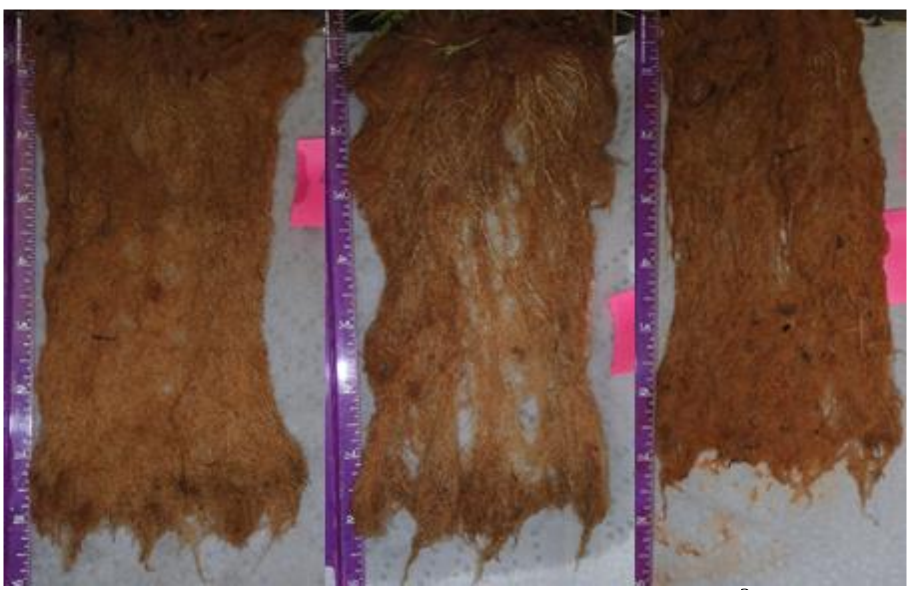

Figure C16 Roots of Mix 2 in bulk density 1.2 g cm^{-3} in three replications**.**