ABSTRACT

BROWN, VIRGINIA KING. Establishing and Maintaining Enhanced Infiltration on Compacted Construction Site Subsoils Through Shallow and Deep Tillage with Soil Amendments. (Under the direction of Richard McLaughlin).

The process of constructing roads and building usually involves the removal of topsoil, grading, and traffic from heavy machinery and trucks handling construction supplies. The result is compacted subsoils with low fertility, which hinder vegetation establishment, limit infiltration and are susceptible to erosion. The goal of this project was to quantify methods for restoring initial and long term perviousness of surface soils compacted by construction equipment by increasing storm water infiltration and accelerating vegetative growth. The study had three locations in North Carolina, the Coastal Plain, Piedmont, and Mountain regions, and evaluates three tillage treatments: a compacted soil and a compacted soil with both shallow tillage (15cm) and deep tillage (30cm). Additional treatments at one or more sites included compost and cross-linked polyacrylamide amendments, and two rates of liming. Runoff quantity and quality was measured at the Piedmont site, and infiltration rate, biomass production, rooting depth, and soil compaction and penetrometer resistance were measured periodically at all sites. Soil compaction and resistance from penetrometer readings indicated root limiting resistance on control plots throughout the profile while tilled soil had minimal resistance or increase to the depth of tillage. Core samples for root analysis at all sites showed short stressed grass roots limited to the upper 5 cm or less on control plots, while vegetation grown on tilled plots had prolific roots. Soil bulk density increased over time on tillage plots, but infiltration rate was not significantly reduced at the Sandhills site, where this infiltration was measured again four months after tilling. Wheel traffic from riding mowers resulted in minimal increases in soil resistance and bulk density in the upper 12 cm

of the profile on tilled plots. Preliminary measurements at the Mountain site on deep tilled plots with riding lawn mower traffic showed unchanged infiltration compared to untrafficked plots. Data from thirteen storm events at the Piedmont site indicated that deep tillage treatments infiltrated 95% or greater of rainfall. Additionally, infiltration tests from all three sites using a Cornell Infiltrometer showed limited infiltration on control plots (0-10%), while tillage resulted in initial infiltration rates near 100%. The results suggest that tillage treatments can greatly reduce runoff from vegetated areas and may provide opportunities to also take in runoff from adjacent impervious areas (Frazer 2005, Richards et al. 2002). Restoring soil porosity and perviousness after construction can be integrated into a storm water management plan to reduce the negative impacts of storm water runoff, particularly in urban areas.

Establishing and Maintaining Enhanced Infiltration on Compacted Construction Site Subsoils Through Shallow and Deep Tillage with Soil Amendments

by
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BIOGRAPHY

Virginia Brown was born in Philadelphia, Pennsylvania on August 16, 1988 and raised in the small town of Cochranville, located in an agricultural area of the state. After graduating from Sanford High School in 2006, Virginia attended the University of Mary Washington in Fredericksburg, VA and graduated in May of 2010 with a B.S. in Environmental Science. Soon after, she began graduate school in Soil Science Department at North Carolina State University.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: LITERATURE REVIEW

When stabilizing a construction site, erosion control best management practices should strive to establish viable stands of vegetation, maximize soil infiltration, minimize storm water runoff and maximize soil health. Soils have the ability to absorb a large amount of rainfall; however, urban soils frequently have low infiltration rates. Soils in urban areas may be compacted for strength or unintentionally compacted due to construction activities (Gregory et al. 2006). When topsoil removal and compaction occur, the result is a surface soil made up of compacted subsoils with low fertility, resulting in poor vegetation establishment, limited infiltration, and susceptibility to erosion. These soils are not often reworked to pre-construction function. Increased areas of impervious surface or compacted soils with low infiltration generate large quantities of water, which often are directed into overburdened storm water systems or stream channels. The detrimental effects on urban stream function from development and the challenges related to restoring degraded streams have been well documented (Booth et al. 1997, Violin et al. 2011). Effectively dealing with storm water runoff volumes is a challenge to many urban municipalities. Tillage has successfully reduced soil compaction and improved infiltration in agricultural settings. These soil improvement practices are not commonly applied on construction sites; the objective of this study was to determine the value of tilling and adding soil amendments to improve the infiltration rate and in turn, reduce storm water runoff.

Soil compaction

Soil compaction caused by construction equipment is a serious problem affecting soil physical properties, including bulk density porosity, and vegetative growth (Randrup et al. 1997). Alberty et al. (1984) documented increased bulk density on construction sites and found densities above 1.4 g cm^{-3}reduced growth of woody plants. Residential, commercial, and roadway construction sites had an average increase in mean bulk density from 1.03 gcm^{-3} on undisturbed soil to 1.56 g cm^{-3} in the construction zone.

Voorhees et al. (1986) studied the degree of soil compaction in an below the typical tillage depths as affected by water content. This study evaluated two clay loam soils with different moisture contents, and compared the bulk density changes under two axle loads, 9 Mg and 18 Mg. Both axle loads increased bulk density in the upper 30cm for the wet Webster soil and significant changes were seen to 60cm with the 18 Mg axle load. Similarly, the wet Nicollet soil had significant increases in bulk density for the upper 15cm. The 18Mg load produced higher bulk densities than 9 Mg; this load also produced differences down to 50cm compared to the control. Conversely, the dry Nicollet soil showed little differences in bulk density between 18Mg and 9Mg throughout the profile.

Wheel traffic intensity also contributes to the degree of soil compaction. Balbuena et al. (2001) studied varying traffic intensity within an Argentinean poplar plantation and concluded that the amount of traffic was directly related to subsequent grassland production. Traffic intensity, measured in Mg km ha^{-1}, was determined by number of passes by logging equipment. Penetration resistance at the surface compared to the untrafficked control increased 54% with one pass and 76% with 10 passes, the highest intensity. Penetration resistance was seen deeper in the profile with more equipment passes. The grass yield from the highest intensity, 10 passes (174 Mg Kg ha^{-1}), was 58.4% less than control, and 40% less with the lowest intensity, one pass (17.4 Mg Kg ha^{-1}).

A study by Jurajuria et al. (1996) found a dramatic 63% yield decrease in grass yield from one pass of a light tractor and 95% decrease in yield from ten passes of a heavy tractor. Cone index (CI) measurements differed significantly from the control and suggest that ten passes of the light tractor (L10) produced equivalent compaction as one pass of the heavy tractor (H1) at the 530-600mm subsoil depth. CI value for L10 was 1897kPa and 1827kPa for the H1 treatment compared to 1202 kPa for the control. Bulk density increases at the same depth were also significant, 1.220 Mg m^{-3} and 1.224 Mg m^{-3} from only five passes of the light tractor and one pass of the heavy tractor respectively.

Lowery et al. (1994) also evaluated axle load effect on bulk density and plant height on a silt loam and silty clay loam. Increases in bulk density were seen within the upper 40cm on both soils. The silt loam bulk density increased from 1.09 Mg m^{-3}at the surface to 1.5 Mg m^{-3} at 40 cm for the control, increasing to 1.34 Mg m^{-3} and 1.63 Mg m^{-}3, respectively, when subjected to a 12.5 Mg axle load. Corn grown during the first year on the 12.5 Mg compacted silty clay soil was on average 36cm shorter than the control, 12cm shorter the second year and still 16cm less the third year. The compacted silt loam soil produced similar reduced mature corn heights, with the highest axle load reducing corn height 36 cm the first year and 13cm the second year.

Reduced root growth has been shown to be a major consequence of soil compaction. Shallow rooted plants are more susceptible to drought stress and also do not provide the deep root channels for water to infiltrate through. Kozlowski et al. (1999) summarized plant responses to soil compaction explaining that roots extend through existing soil pores or by displacing soil particles. After compaction the amount of available air filled pore space decreases and soil strength increases. When soil strength exceeds a root's ability to expand smaller sized pores, root growth is redirected and growth rate or elongation decreases. Gilman et al. (1987) studied the rooting habit of *Ailanthus altissima* and noted increased lateral branching and thicker and shorter roots of the plants grown in compacted soil. Using a cone tipped penetrometer, Taylor et al. (1969) concluded that soil strength between 2.5 and 2.96 MPa, due to either an increase in bulk density or decrease in soil moisture, was impenetrable by roots. Alberty et al. (1984) studied woody plant growth on soils with low (1.21 g cm^{-3}) high (1.31 g cm^{-3}), and control (1.05g cm^{-3}) levels of compaction. Replicated experiments were performed on plots using *Cornussericea* and *Forsythia ovata.* Although the high levels of compaction seen on construction sites were not achieved on test plots, *Forsythia* still had significantly decreased height growth on both compacted treatments compared to the control. *Cornus* growth on compacted soil was not significantly different from the control. There was a trend towards lower shoot and root dry weight with increased compaction for both species, although not significant.

Plants and Infiltration

Strong stands of vegetation above ground protect the soil surface from erosion. Plants are also a key component of the water cycle since roots create and provide channels for infiltrating water (Bouma et al. 1977).

Research by Meek et al. (2002) demonstrated that alfalfa crops grown on compacted soils increased infiltration over a period of four years. Without crop cover, an increase in soil bulk density from 1.6 Mg m^{-3} to 1.8 Mg m^{-3} resulted in a 53% reduction in infiltration. The four year study included alfalfa grown on three compaction levels: light, medium, and heavy, corresponding to bulk densities of 1.76 Mg m^{-3}, 1.88 Mg m^{-3}, and 1.96 Mg m^{-3} respectively. Similar densities were measured four years later, but over the course of the study, infiltration increased 442% on the light compaction treatment and 534% on the heavy compaction treatment compared to paired measurements made the first year.

Hino et al. (1986) concluded that a developed root system outperforms bare soil in reducing runoff, increasing infiltration, and maintaining uniform soil moisture. Rainfall simulation tests demonstrated that even under a rainfall rate of 100 mm h^{-1}, the grassed plots did not produce overland flow. The vegetated treatments had both high saturated conductivity and storage capacity. The large root channels provided characteristics of a sandier soil, while the inherent high water storage of the loam clay soil was preserved. Approximately one third of infiltrated water was transported through the profile to groundwater and the rest was lost to evapotranspiration. Conversely, the bare plots lost on average 60% of rainfall as overland flow. Additionally, uniform moisture loss, regardless of depth, was observed on grassed plots compared to bare plots, which showed significant drying at the surface.

Similarly, Bartens et al. (2008) investigated how tree roots might enable and enhance infiltration on compacted urban soils. The greenhouse study measured infiltration and root distribution for 2yr old bare root red maple and black oak trees transplanted on clay subsoil compacted to two levels, 1.31 g $cm^{-3}$and 1.59 g cm^{-3}. Trees increased infiltration on the high compaction level compared to no trees by 153%. At all levels of compaction, infiltration on pots with trees was on average 63% greater than pots without trees. Root distribution for both species was not altered by compaction level, indication that tree roots are able to penetrate highly compacted soil. Alternatively, Bengough et al. (1991) found a negative correlation between root elongation and penetration resistance, with a 50% decrease in root elongation in compacted soil compared to the control. Chen et al. (2009) compared the penetrating abilities of fibrous and tap rooted plants on compacted soil. The tap-rooted species, forage radish and rapeseed, were the least affected by compaction and showed two or more times the number of roots compared to rye grass. Reductions in soil compaction and increased infiltration attributed to plants have important implications to soil remediation practices after construction. Amending the soil in a way to encourage strong stands of vegetation may aid in accomplishing long term infiltration on a site.

Tillage

Tillage provides immediate porosity to the soil profile, allowing for plant roots to easily develop and extend and well as rapid infiltration of water at the soil surface. Tillage depth is related to infiltration rate and generally the deeper the till, the greater the water storage capacity. Additionally, infiltration rate after tillage is influenced by ground cover and traffic. Maintaining a high infiltration rate over time is an important component of managing storm water.

Varsa et al. (1997) studied the effects of three tillage depths, 40 cm, 60 cm, and 90 cm on soil physical properties over a period of four years. Penetrometer resistance, bulk density, rooting density, and grain yields were monitored over four years of corn production. Prior to tillage treatments, subsoil penetration resistance for all plots averaged 2.5 Mpa. After tillage, penetration resistance decreased with all the three tillage depths within the first year. Only the 90 cm treatment maintained low resistance values between 0.5 Mpa and 1.6 Mpa within the upper 80 cm of the profile over four years. Bulk density measurements were not reduced significantly at any depth for the 0 cm, 40 cm, and 60 cm treatments. Bulk density measurements for the 90 cm treatment were less than all other treatments over four years. The 90cm tillage depth significantly reduced soil bulk density from 20-80 cm compared to the control and 40 cm and from 40-80 cm compared to the 60 cm till.

Lipiec et al. (2005) demonstrated that tillage significantly affected the pore size distribution, with pores (>117 um) accounting for 10.34% of the area on the conventional till compared to 6.17% on the non tilled treatment. The cumulative infiltration in a double-ring infiltrometer after three hours on the conventionally tilled treatment was 94.5 cm, while the reduced till and no till treatments infiltrated 36-62% less. Radcliffe et al. (1988) performed a similar study using a sprinkle infiltrometer and noted that the formation of a surface crust greatly influenced infiltration on both non tilled and conventional tilled plots. Runoff was minimal after one hour, sprinkling rate of 70 mm h^{-1}, when surface mulch was applied to the tilled treatment. Conversely, even with surface cover, infiltration decreased after 45 minutes on the no till plot. A sprinkle infiltrometer was also used by Freese et al. (1993) and it was concluded that wheel traffic significantly reduced infiltration compared to non trafficked rows for both tilled and non tilled soil. Jones et al. (1994) evaluated runoff and infiltration on a no till and a stubble mulch till treatment. The stubble mulch treatment had 62% and 90% greater infiltration than no till for the first and second hour.

Soil Amendments

Establishing ground cover after construction is imperative for reducing soil erosion; amending soil with compost has been shown to positively influence both soil physical properties and plant growth. Bazzoffi et al. (1998) conducted a study on a clay loam soil evaluating the effects of urban refuse compost on erosion and soil physical properties. Compost was spread over a tilled surface and then harrowed to incorporate. Reduced runoff volume on compost plots during both the growing and non growing season was observed in all three years. Statistically significant runoff decreases were observed for both the second and third years during the growing season, 17.3% and 26.4% respectively. Runoff was reduced over 50% during the second year of the non growing season, 372.08 m^3 ha^{-1}

compared to 772.22 m^3 ha^{-1} on non composted plots. Total erosion measurements for bare seed-bed soil conditions were also lower in all three years for the compost treatment. In a study by Cox et al. (2001), compost was incorporated before planting a barley crop. Reductions in bulk density were found at all sampling times and significantly so during the second spring, with 1.43 g cm^{-1} on the control and 1.14 g cm^{-1} with compost. Barley yields (kg ha^{-1}) were also significantly greater (24%) on composted plots.

Improved infiltration and changes in saturated hydraulic conductivity were observed in a compost experiment by Curtis et al. (2007). Compost was mixed at three rates (6%, 12%, and 24%) to a highly erodible decomposed granite saprolite soil located on a roadside cut slope. Significant increases in saturated hydraulic conductivity were observed at the 12 and 24% compost rate. No differences among treatments were found one year later when the sites had well established vegetation. However, the 12% and 24% compost treatments had significant increases in hydraulic conductivity the second year compared to the first. Significant increases from year one to year two of 38 mm h^{-1} to 46 mm h^{-1} at the 12% rate and 47 mm h^{-1} to 60 mm h^{-1} at the 24% compost rate were observed.

Linear polyacrylamide (PAM) has been used in arid agricultural regions to increase the efficiency of irrigation systems by reducing furrow erosion and improving infiltration and (Trout et al. 1995). Super absorbent cross-linked polymers have been used to increase water holding capacity and lower hydraulic conductivity in excessively drained sandy soils, but few studies have been conducted on their effectiveness. Yu et al. (2011), using soil from the semi arid Northwest region of China, evaluated soil water retention using four cross linked PAM's with varying grain size on three soils (loamy sand, sandy loam, and sandy clay loam). Water retention curves indicated that the amount of water absorbed by the PAM decreased with increasing clay content, suggesting potential applications on sandy soils with low water retention. Additionally, PAM granule size influenced the total amount of water absorbed and both the time needed for the polymer to fully swell and dry. Small granule PAM reached maximum absorption in 10 to 20 minutes compared to 50 to 60 minutes for the larger grain size. Water content in soils amended with smaller granule size PAM also showed a distinct decrease after the polymer reached maximum absorption, where treatments with the large granule size displayed a more gradual and consistent curve.

A greenhouse study by Agaba et al. (2010) found pine seedlings grown in sand with the highest rate of polymer (0.4% by volume) survived twice as long as control seedlings. Additionally, seedlings grown in amended soil had approximately three times the root and shoot growth of the control. Polymers were tested in an irrigated tomato production study by Johnson et al. (1996). Fruit quality and shoot dry weight were evaluated for plants grown on two soils amended with three cross linked polymers. Polymer amendments to the sand soil resulted in significantly higher shoot dry weights and fruit production compared to the sand control. Polymer amendments to the compost soil did not increase shoot dry weight and had minimal influence on fruit production. The number of marketable tomatoes was greater for plants grown on both soils with added polymer compared to the controls; for the sand soil, the PAM addition resulted in twice the fruit yield of the sand control. The benefit of added polymer was greater on sandy soil than the highly organic compost soil.

A study by Busscher et al. (2009) evaluated both linear and cross linked polyacrylamide in a three year field study on sandy coastal plain soils. Three rates of each polymer were applied behind a subsoiler and compared to control treatments of subsoiling alone and not subsoiling were included. Cone index, water content, and maize yield were recorded. Tillage had the most effect on yield response and none of the PAM treatments resulted in significant increases plant response or changes to cone index. Any small changes due to the addition of cross linked polymer did not last over time.

CHAPTER 2: PIEDMONT, SANDHILLS, AND MOUNTAIN SITE EXPERIEMNTS

MATERIALS AND METHODS

Raleigh Construction sites Sampling

In order to form a baseline for the soil conditions on sites post construction, thirteen newly developed sites in the Raleigh area were sampled for bulk density and soil texture. Infiltration rate, using a Cornell Sprinkle Infiltrometer (Cornell University, Ithaca, NY), was measured at three of the sites. Equivalent data was collected at three additional sites for comparison: a 20yr home with established lawn, a 50yr pine forest, and an ungrazed meadow.

Plot setup (all plots)

The topsoil and vegetation were removed from a 330 m x 15 m area at each site 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 from equipment traffic on construction sites, the graded area was further compacted by repeated passes with a smooth drum vibratory roller, Figure 1 (Hertz Equipment Rental, Raleigh, NC; 12ton Piedmont, 8 ton Sandhills, 10 ton Mountain). Bulk density samples from the upper 10cm were taken using a 2” soil core sampler (AMS Inc., American Falls, ID) The upper 2.5cm ring from each sample was discarded. Samples were oven dried at 105ºC and weighed were then taken to determine the compaction level and particle size analysis was also done using the hydrometer method (Gee and Bauder, 1986). Soil samples were sent to the North Carolina Department of Agriculture and Consumer Services for analysis for lime recommendations.

Figure 1. Smooth drum vibratory roller used for compaction.

Soil Properties

Table 1. Particle size analysis for all sites using the hydrometer method.

	Site		
Particle Size Fraction	**Piedmont**	**Sandhills**	**Mountain**
Sand	48	92	48
Silt	12	6	22
Clay	40	2	30

Table 2.Soil test nutrient recommendations from NCDA&CS for all sites.

	Nutrient Requirement (lb/1000ft^2)		
	Site		
Parameter	**Piedmont**	**Sandhills**	**Mountain**
N	1	1.5	1
P	2	0	0
K	2	1.5	0
Lime	25	32	0
Soil pH	5.8	6	6

Piedmont Site

The site was installed on February 22, 2011at the NCSU Lake Wheeler Field Laboratory, Raleigh, NC. The plot area was located on a southwest facing hillside. Three tillage treatments were tested at this site and will be represented by the following abbreviations, a control with no tillage (C), shallow till (15cm;ST), and deep till (30cm;DT). After grading and compaction, the area was divided into four 14m x 6 m blocks with a 2.5 m buffer between adjacent blocks with treatment plots arranged in a randomized, complete block design (Figure 2). For storm water collection and drainage, a 1 m deep by 1.5 m wide ditch was dug separating the two upslope blocks from the down slope blocks and a second ditch below the two lower blocks. Additionally, a small trench around the perimeter was created to prevent outside water from running onto the experimental area. The blocks were randomly subdivided into three sections for the three tillage depths, with 4ft in between; two 3.6m x 6 m sections for ST and compacted and one 4.3 m x 6 m section for DT. The perimeter of each tilled plot was outlined using a trencher to prevent areas outside the plot area from damage during the initial excavation portion of the treatment. Prior to tilling, a backhoe initially broke up the compacted soil surface to allow the tilling equipment to penetrate to the needed depths (Figure 3). Repeated passes using a tractor mounted rotary tiller accomplished a till depth of approximately 15cm or 30 cm. A commercial 10-20-20 fertilizer was applied at 1000 kg ha^{-2} for all treatments. For each ST and compacted plot, the areas were subdivided into two sections; one half received no lime and the other half received 1250 kg ha^{-2}. The DT plots were subdivided into three sections and randomly assigned one of the following lime application rates: 0, 1250, and 2500 kg ha^{-2} (Figure 4). One or two additional passes of the tiller incorporated the lime and fertilizer on the tilled treatments only. Following North Carolina Department of Transportation recommendations (Roadside Environmental Unit, Vegetation Management), a grass seed blend of *Festuca brevipila* (hard fescue), *Poa pratensis* (Kentucky bluegrass), and *Secale cereal* (rye grain) was applied by hand at a rate of 134 kg ha^{-1}, raked in, and covered with straw, at a rate of 4500 kg ha^{-1}. The plots were temporarily covered with 6 x 12 m sheets of woven jute fabric stapled in to prevent wind from blowing the seed and straw. This fabric was removed a few weeks after germination.

Plots were reseeded with fescue at 240 kg ha^{-2} and fertilized with 50 kg N ha^{-2} in October to help fill in bare or sparse areas.

Figure 2: Map of the Piedmont site (Google Map).

Figure 3. Breaking up the soil before tillage.

Figure 4. Three liming rates on a DT plot at the Piedmont site.

Sandhills Site

The Sandhills site was installed on August 16, 2011, with site preparation in the similar to that at the Lake Wheeler site. No drainage ditches were dug as storm water runoff was not collected at this site. The area was divided into a rectangle with four 14 m x 6 m blocks in a row from north to south and a 3 m buffer between adjacent blocks. The blocks were randomly subdivided from east to west into three sections for the same three tillage depths used at the Piedmont site, with 1.5m in between. Treatments were control (C), control + compost (CC), shallow till (ST), shallow till + compost (STC), deep till (DT) and deep till + compost (DTC), each described below. The 30 cm tillage depth (DT) was achieved by first passing over the area with a multi-shank subsoiler/ripper (Figure 5) followed by rotary tillage (

Figure 6). The rotary tiller was sufficient to till the 15cm depth plots (ST). Both nitrogen and potassium were applied at 78 kg ha^{-1} for all treatments. For each ST and C plot, the areas were subdivided into two sections; one half received no lime and the other half received 1500 kg ha^{-1}. The DT plots were subdivided into three sections and randomly assigned one of the following lime application rates: 0, 1500, and 3000 kg ha^{-1}. An additional pass of the tiller incorporated the lime and fertilizer on the tilled treatments only. A 5 cm surface layer of compost application was added to each tillage treatment; this was left on top of compacted plots and incorporated into the upper 15 cm along with lime and fertilizer on the tilled plots. Compost was obtained from Novozymes North America Inc. (Franklinton, NC) and the Erosion Control 1.2cm sieve size was used (pH 7.6, C:N 14.5). *Festuca arundinacea* (tall fescue) and *Cynodon dactylon* (Bermuda grass) were hand seeded and raked in directly after fertilizer and lime application. The upper half of each plot was seeded with fescue at 300 kg ha^{-2} and the lower half was seeded with Bermuda grass at 65 kg ha^{-2}. Straw was applied at 3400 kg ha^{-1} and held in place by thin twine stretched cross wise across the plot and stapled in.

Plots were reseeded with tall fescue in January 2012 at 145 kg $ha^{-2}$and fertilized with 50 kg ha^{-2} N and 100 kg ha^{-2} K for maintenance top fill in areas with poor stands.

Figure 5. Subsoiler used on DT plots at the Sandhills site.

Figure 6. Incorporation of amendments using a rotary tiller.

Mountain Site

This site was installed on October 13, 2011. After excavation and compaction, similar to the other sites, the 330 x 15 m area was subdivided into four blocks in a row from North to South with a 1.5 m buffer section between adjacent blocks. The blocks were randomly subdivided from east to west into three sections for the three tillage depths, with 0.5 m in between. The same tillage treatments used at the Sandhills site were used here: control (C), control + compost (CC), shallow till (ST), shallow till + compost (STC), deep till (DT) and deep till + compost (DTC). On the 30 cm tillage plots, a backhoe initially loosened the soil before using a rotary tiller. A subsoiler set at 15 cm was used in addition to a rotary tiller on the ST plots. The soil test indicated that no lime was needed for fescue grass. Nitrogen was applied at 50 kg ha^{-2} to all plots. On 1/3 of the tillage plots, granular cross linked polyacrylamide (Aquasorb, SNF Inc.) was surface applied as an additional treatment to both the 15 and 30 cm till plots at 320 kg ha^{-2}. The polyacrylamide was then tilled into the surface to a 15 cm depth. On another 1/3 of the tilled plots, a 5 cm compost application was added to each tillage treatment; this was left on top of C plots and incorporated into the upper 15 cm along with fertilizer on the DT and ST plots. There was not enough compost for all planned treatments so it was not applied to the DT treatment in blocks one and two. The same compost used at the Sandhills site was used, obtained from Novozymes North America Inc. (Franklinton, NC). *Festuca arundinacea* (tall fescue) seed was spread by hand at 290 kg ha^{-2} and then covered with straw at 3300 kg ha^{-1}. In November, bare areas were uniformly reseeded to ensure good coverage. Plots were fertilized with 5 kg ha^{-2} N in February 2012.

Seed Testing

Seed germination tests were conducted to ensure quality and viability of seed using the methods from *The Journal of Seed Technology*. The following seeds were tested: *Poa pretensis* (Kentucky bluegrass), *Festuca trachyphylla* (hard fescue), and *Secale cereal* (rye grain) for the Piedmont site, *Cynodon dactylon* (Bermuda grass) and *Festuca arundinacea* (tall fescue) at the Sandhills site, and *Festuca arundinacea* (tall fescue) at the mountain site. The seed was purchased from Green Resource (Garner, NC) and Wyatt Quarles Seed Company (Garner, NC). Fifty seeds of a single variety were arranged on a moistened growth medium in a petri dish and incubated using a Hoffman germinator (Figure 7). Three replications of each variety were done. The Kentucky bluegrass, tall fescue and hard fescue were germinated at 15ºC/25ºC, with germination counts at 10 and 28 days and 7 and 21 days respectively. The rye grain seed was rolled in wetted towels and germinated at a constant 18ºC with counts at 4 and 7 days. Bermuda grass was germinated at 20ºC/35ºC, with germination counts and 7 and 21 days. The non viable rye grain seeds showed fungal and bacterial growth at day 7. Germinated seeds were recorded and removed at each count date.

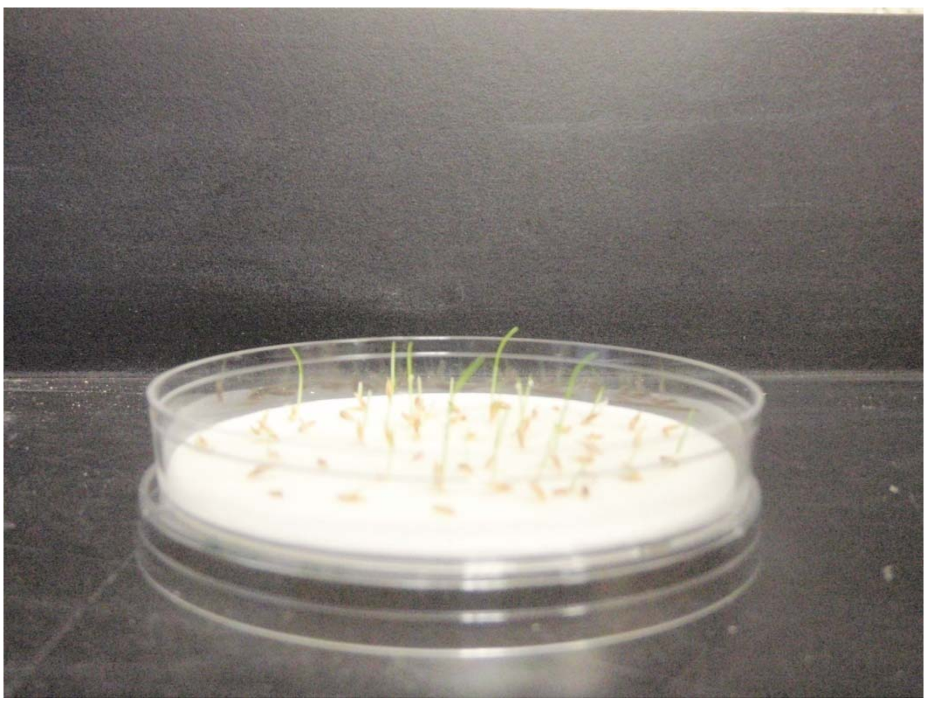

Figure 7. Seed germination testing.

Bulk Density and Compaction

To determine the amount of compaction created from traffic, bulk density samples were taken before implementing tillage treatments. An AMS 2” soil core sampler (AMS Inc., American Falls, ID) was used to collect 10 cm x 5 cm cores of the upper profile. The upper 2.5cm ring from each sample was discarded. Samples were oven dried at 105ºC and weighed. Directly after tilling, bulk density samples from ST and DT plots were taken. Repeated samples were taken at 10 months after establishment at the Piedmont site, five months at the Sandhills site, and four months at the Mountain site to document changes over time.

Evaluation of soil compaction from 0 to 30 cm was also determined by using a cone tipped penetrometer (FieldScout SC 900 Soil Compaction Meter, Spectrum Technologies Inc.). Three test areas from each individual tillage plot were averaged for a single resistance profile for each treatment. At the Piedmont site, measurements were made in March, April, May, July, and January; each sampling was made after a rain storm when the soil was at field capacity. To study the extent of compaction from wheel traffic, half of each ST and DT plot was passed over three times with a riding lawn mower (John Deere 777 Ztrak, 177 kPa). Soil moisture at the time of compaction averaged 0.31 cm^3 cm^{-3} in January. Resistance measurements using the same cone tipped penetrometer and repeat bulk density samples were made in January at the Sandhills site and in March at the Mountain site. Penetration and bulk density measurements were also made after wheel traffic was introduced to the Mountain plots in April at soil moisture content of 0.13 cm^3 cm^{-3} (John Deere 455, 90 kPa). Mower traffic was again repeated in May when the soil moisture was 0.28 cm^3 cm^{-3}. Wheel traffic treatment was not added as a treatment at the Sandhills site.

Above Ground Biomass (all sites)

Biomass collection was performed after approximately 3 months of growth or until a uniform stand of grass was established. A 1m x 1m PVC frame gridded into 25 20 cm^2 sections was used to collect and measure biomass ( ). Three 20 cm2 squares were randomly chosen and all the grass to the ground surface was clipped with scissors. This was repeated three times for each treatment at the Piedmont site, for a total of nine 20 cm^2 sections. Three 20 cm^2 sections were clipped from the Sandhills and mountain sites. Clippings from each plot were combined and oven dried at 105 ºC and weighed. An estimate of biomass (kg ha^{-1}) for the total plot area of all plots was determined from the weight of vegetation over total area clipped. Vegetative cover estimates at all three sites were determined from digital plot photographs using the GIS program ArcMap (Figure 9).

Figure 8. Grid used for above ground biomass measurements.

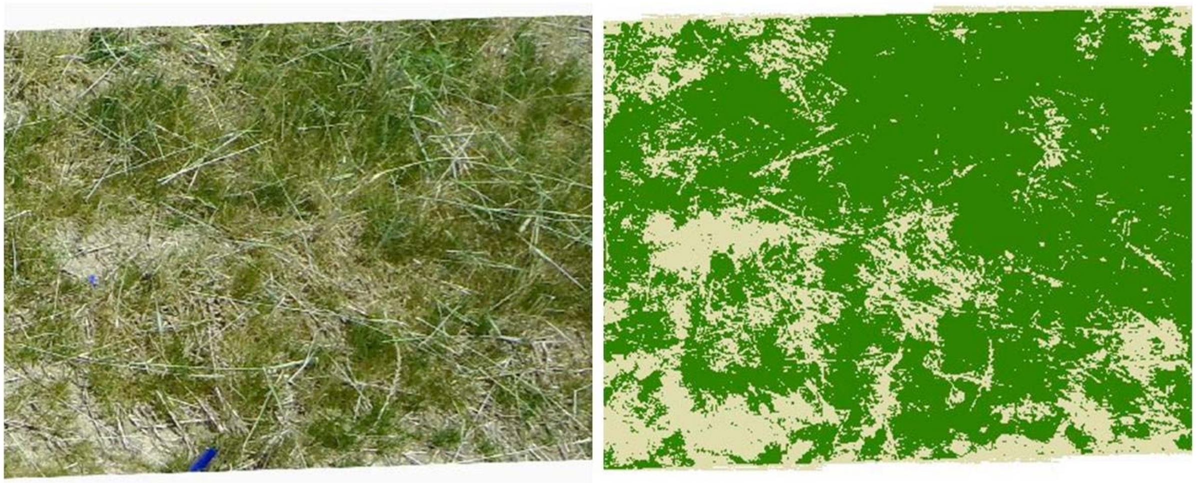

Figure 9. GIS photo used to estimate vegetative cover.

Rooting

Root measurements were made for each treatment at all sites at approximately the same time above ground vegetation measurements were made. The same AMS soil core sampler used for bulk density was used to collect samples for rooting measurements. 30 cm of the profile were collected in two sections, the upper 15 cm and a second coring in the same hole for the lower 15 cm. At the Sandhills site, a 3 ¼” soil auger (Figure 10) was used in place of the AMS sampler due to difficulty coring the sandy texture. Roots were extracted by washing away the soil 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) (Figure 11); photographs of each rooting profile were taken for visual comparisons.

Figure 10. Soil auger used for taking root samples at the Sandhills site.

Figure 11. Washing soil to extract roots.

Infiltration

A Cornell Sprinkle Infiltrometer (CSI), (Cornell University, Ithaca, NY) was used to estimate infiltration rate at all sites for each treatment. Infiltration measurements were made directly after tilling and after vegetation establishment at the Sandhills and mountain sites. At the Piedmont site, measurements were taken approximately three and a half months after planting and were not made after initial tilling. The CSI ring was positioned on relatively flat area with uniform ground surface and pounded into the ground placed so the runoff exit opening on the ring was level with the ground surface. The CSI was then filled and set on top of the ring; a rainfall rate between 20 and 60 cm hr^{-1} was set for each plot and allowed to run until a constant rate of runoff was achieved. Runoff was collected into a beaker, subset in a small hole, and measured every minute, lower rates were used on compacted sites to reduce runoff volume. If the soil was dry, the area was saturated with a hose for several minutes before using the CSI. To determine infiltration rate, Equation 1, calculated the difference between the water volume used during the test and the amount of runoff:

$$\text{Equation 1: } i_t = r - ro_t$$

i_t= infiltration rate

r = rainfall rate = [H1-H2]/T

ro_t = runoff rate = V_t / (457.30*t)

Data 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 MIXED procedure was performed on all data to analyze main effects and was used to separate treatments. Significant differenced were measured at α=0.05, unless otherwise noted.

RESULTS AND DISCUSSION

Bulk Density and Infiltration on Newly Developed Sites

Bulk density samples from recently developed (1-3 yrs) sites near the Piedmont are shown in Table 3. At sites 1-4, bulk density measurements were taken at 0-15 cm and 15-30 cm. Deeper in the profile the bulk density remained the same or increased with depth, perhaps due to traffic that occurred on the soil when it was wet, as reported elsewhere

(Vorhees et. al 1985). Infiltration could not be detected at sites 10 through 13, recently developed areas, while 100% infiltration was measured on both the meadow and forest sites for irrigation rates of 39 and 30 cm hr^{-1} respectively. The older established lawn, adjacent to the meadow, had a reduced infiltration rate compared to the meadow. A very thin or absent A horizon was evident on the newly developed sites, while a thick 12-14 cm A horizon existed the meadow site. Recently developed sites were characterized by having a poor grass cover or sod over subsoil. The older lawn had approximately 6 cm of organic material on the surface. The compacted surface layers produced runoff just several minutes after irrigation began, indicating that soil water storage would likely be limited by surface infiltration rate. The highly porous and organic surface layer of the forest and meadow prevented surface ponding and allowed for rapid infiltration into the soil profile.

Table 3. Bulk density and infiltration rates from newly developed, establish lawn, meadow, and pine forest sites around Piedmont.

Site	Soil Texture	Bulk Density ($g\ cm^{-3}$)		Irrigation	Infiltration
		0 -15 cm	15 – 30 cm	($cm\ hr^{-1}$)	
1	Clay	1.3	1.5		
2	Clay	1.8	1.8		
3	Clay	1.4	1.4		
4	Clay loam	1.3	1.5		
5	Clay loam	1.4			
6	Clay loam	1.5			
7	Clay	1.5			
8	Sandy loam	1.7			
9	Clay	1.3			
10	Sandy clay	1.5		56	0
11	Sandy clay	1.9		44	0
12	Sandy clay	1.5			
13	Sandy clay	1.6		44	0
20yr lawn	Sandy loam	1.3		38	12
Meadow	Loamy sand	1.2		39	39
50yr pine	Sandy loam	1.4		30	30

Bulk Density and Compaction

Piedmont Site

Samples taken after compaction had an average bulk density of 1.5g cm^{-3} in the upper 15 cm and 1.6 cm^{-3} at the 15-30 cm depth. These values are comparable to other studies of construction activity effects on finer textured soils (Alberty et al. 1984, McNabb 1993, Yang et al. 2011). Immediately after tillage, soil bulk density was reduced significantly to 1.1 g cm^{-3} in the upper 15 cm on the DT and ST plots. Bulk density samples were not measured at the

15- 30 cm depth on either treatment. Numerous studies have documented the decrease in bulk density as a result of tillage in agricultural settings (e.g. Chen et al. 2004, Islam et al. 1994). Repeat bulk density sampling in January 2012 resulted in slightly higher mean values for the DT and ST plots; this increase was attributed to soil settling and was statistically significant only on ST plots. Added wheel traffic in January further compacted the soil, significantly increasing bulk density on DT plots compared to both February 2011 and January 2012 measurements. Wheel traffic did not significantly increase bulk density in ST plots when compared to January 2012 measurements (Table 4).

Soil resistance in the DT plot was low throughout the 30 cm profile (<1Mpa), while soil resistance increased below 15 cm on the ST plots and remained high and root limiting (> 2.5Mpa) from the surface to 30 cm on the compacted plots (Figure 12). Despite a significant increase in bulk density from traffic, the DT treatment maintained low resistance throughout the profile (<1Mpa). This was well below the root limiting resistance of 2.5Mpa (Taylor et al., 1966; Taylor and Burnett, 1964). Soil resistance increased below 15 cm on the ST plots and was high (> 2.5Mpa) from the surface to 30 cm on the compacted plots. Figure 13 illustrates changes in soil resistance attributed to riding lawn mower wheel traffic. Compaction from the riding mower increased resistance slightly in the surface 15 cm of the ST and DT treatments, but this effect was not evident deeper in the profile.

Table 4. Average pre-and post-treatment and post-treatment bulk density measurements from the Piedmont site.

Treatment	**Surface Bulk Density (g cm^{-3})**		
	February 2011	**January 2012**	**January 2012 + traffic**
C	1.5a^{a}	1.5a^{a}	1.5a^{a}
ST	1.1b^{a}	1.3b^{b}	1.4b^{b}
DT	1.1b^{a}	1.2b^{a}	1.3b^{b}

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

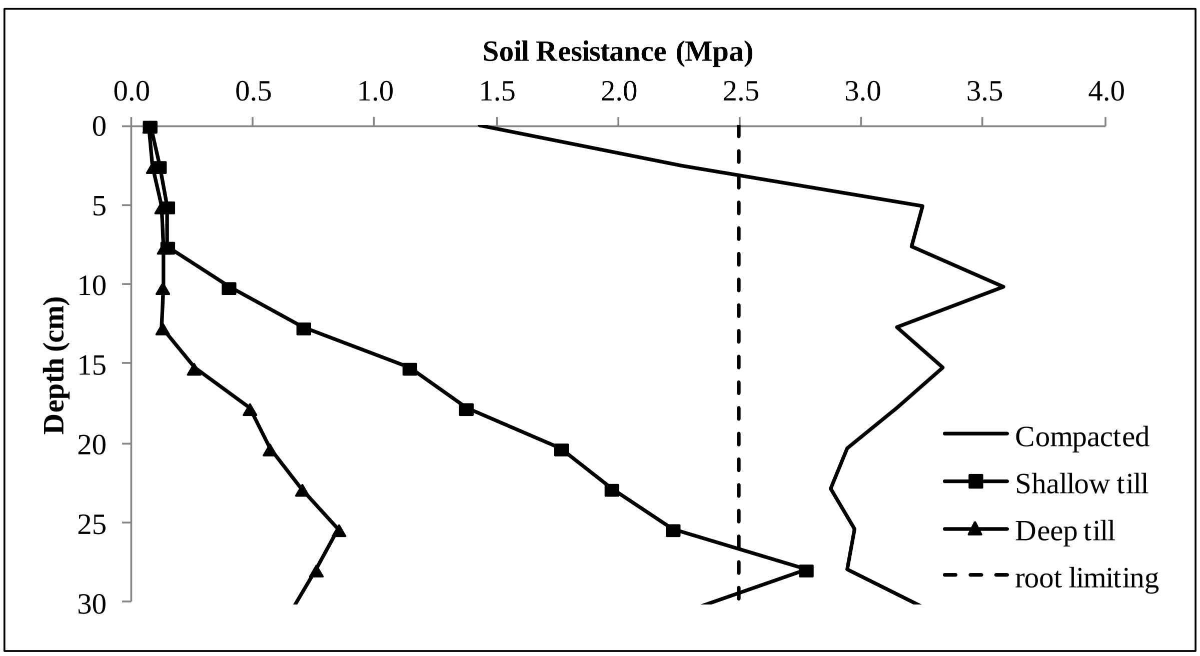

Figure 12. Soil resistance measured on April 12, 2011 with a penetrometer, Piedmont site.

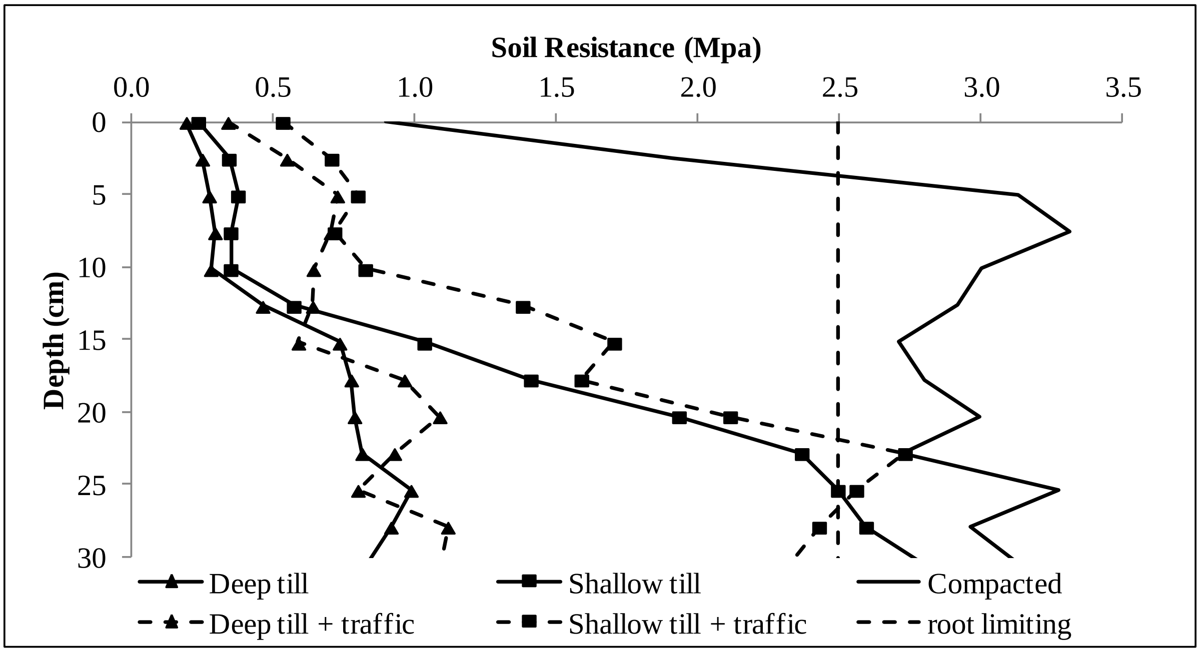

Figure 13. Soil resistance with added wheel traffic, measured on Jan. 23, 2012 Piedmont site.

Sandhills Site

Bulk density measurements taken soon after tilling and then five months later show changes attributed to vegetation and time (Table 5). Measurements were taken from the upper 15 cm only. Soil bulk density after mechanical compaction was 1.9 g cm^{-3}; tillage significantly reduced soil density in the upper 15cm to 1.1 g cm^{-3}. The DT and ST plots with incorporated compost had lower mean bulk densities both initially and after 4 months. Soil settling from August to January significantly increased bulk density on tilled plots. Conversely, bulk density dropped significantly from 1.9 g cm^{-3} to 1.8 g cm^{-3} on C plots, most likely due to grass growth and rooting. However, all tillage treatments were still significantly lower than the C on the January sampling date. Resistance measurements were well below rooting inhibition levels (< 1Mpa) for nearly the entire profile of the DT plots. Resistance increases considerably on ST plots below 15 cm. The compacted plots maintain high and root limiting resistance values (>2.5Mpa) from 5 to 30 cm, with lower values close to the surface where grass roots likely loosened the soil (Figure 14). The positive effect roots had near the surface are not likely occur deeper in the profile since environmental factors such as precipitation, which also aided in loosening the soil for plant roots, only influence the top few centimeters of the soil surface.

Table 5.Average bulk density measurements from the Sandhills site.

Treatment	**Surface Bulk Density (g cm^{-3})**	
	August 2011	**January 2012**
C	1.9 a^{a}	1.8 a^{b}
ST	1.1 b^{a}	1.5 b^{b}
DT	1.1 b^{a}	1.5 bc^{b}
ST + compost	1.0 b^{a}	1.4 c^{b}
DT + compost	1.0 b^{a}	1.4 bc^{b}

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

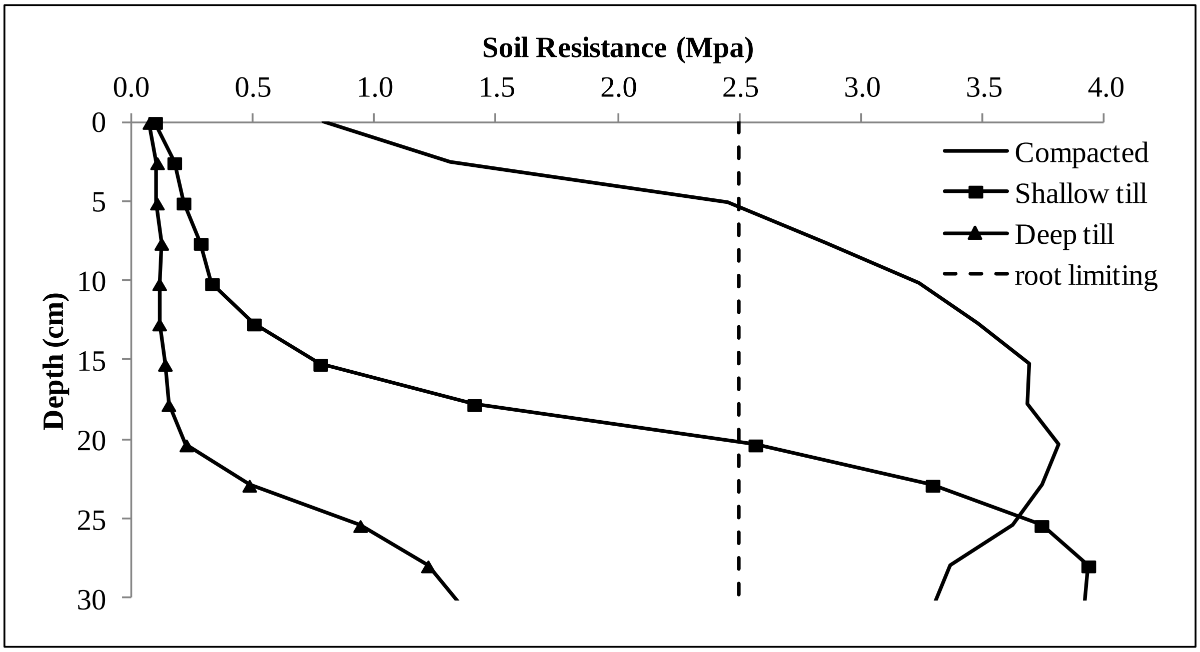

Figure 14.Soil resistance measured on January 31, 2012 with a penetrometer, Sandhills site.

Mountain Site

Penetration resistance through the profile shown in Figure 15 closely resembles the data from both the Piedmont and Sandhills site. Tillage significantly reduced the bulk density, immediately after plot set up, within the upper 15 cm of the profile. Bulk density samples from 15 – 30 cm were not taken. The addition of wheel traffic in April 2012 consisted of two passes at a soil moisture of 0.19 cm^3 cm^{-3} did not significantly increase soil bulk density. Soil moisture content at this site was lower than at the Piedmont site when traffic was added. Wet soil is more prone to compaction, however at the Piedmont, the soil profile was minimally impacted in terms of penetration resistance. Insignificant bulk density changes at the Mountain site suggest that tilled soils have the potential to maintain infiltration rates and low bulk densities with light traffic.

Table 6.Average bulk density measurements from the Mountain site.

	Surface Bulk Density (g cm^{-3})		
Treatment	**October 2011**	**April 2012**	**After Mower Compaction**
C	1.5a	1.4	1.4
ST	1.1b	1.14	1.15
DT	1.0b	1.0	1.1
ST + compost	.7c	1.0	1.1
DT + compost	.6c	1.0	1.0

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

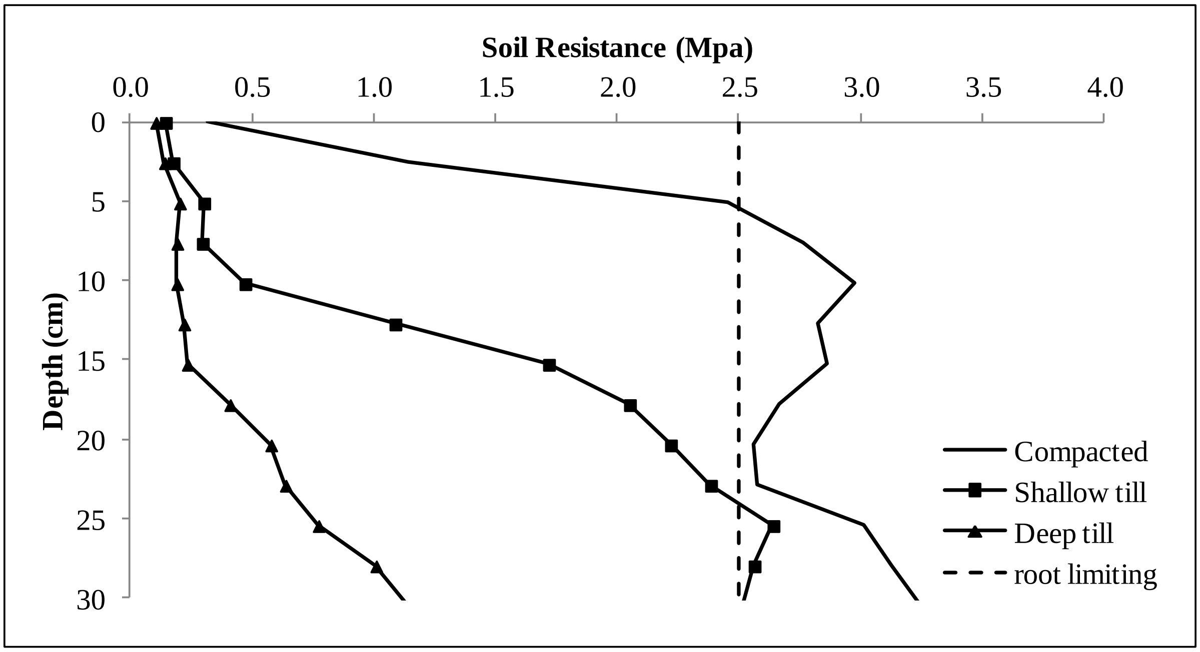

Figure 15. Soil resistance measured on March 6, 2012 with a penetrometer, Mountain site.

Biomass

Piedmont

Both GIS estimated coverage and biomass measurements taken 4 months after planting indicated tillage significantly improved grass growth (**Table 7**). The above ground vegetation mass of the C treatment was 40% less than that of either the ST or DT treatments. Similarly, coverage estimates were 42% on the C plots compared to 62% and 56% for ST and DT treatments, respectively.

Table 7. Biomass measurements at the Piedmont site, June 2011.

	Surface Biomass	
Treatment	**g m^{-2}**	**GIS estimated % cover**
C	946a	42a
ST	1597b	62b
DT	1566b	56b

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

Sandhills

Above ground biomass measurements at the Sandhills site were made in November, approximately three months after planting. Grass growth was relatively poor, around thirty times less than the yield at the Piedmont site, and few differences were found among the treatments. The addition of compost did not significantly improve grass growth on the C and DT plots (Table 8). Separate averages for tillage treatments + liming rate are not included in the table as they did not show any difference; biomass averages for C, ST, and DT include all liming rates (0, 1x lime, and 2x lime for DT). No significant differences in grass yield were seen from lime incorporation on the tillage treatments and surface applied to C plots. The lack of response from lime application was probably due to a starting pH of 6 and little need for additional lime.

Biomass coverage estimates made in May 2012 indicate that surface applied compost on the compacted C significantly hindered grass growth and resulted in poor coverage, 46%.

The surface applied compost layer on the C treatment appeared to inhibit grass germination; the organic mulch material perhaps became hydrophobic and slow to saturate when dry (Faucette et al. 2004). Compost incorporation on the deep tillage plots resulted in higher percent coverage, statistically greater coverage than the controls and the ST treatment.

Table 8.Biomass measurements at the Sandhills site.

Treatment	Surface Biomass	
	November 2011 ($g\ m^{-2}$)	May 2012 GIS estimated coverage %
C	39a	62b
C + compost	30a	46a
ST	39a	63b
ST + compost	58a	74bc
DT	33a	72bc
DT + compost	20a	80c

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

Mountain Site

Due to a proliferation of wheat growth from the straw mulch ground cover applied at seeding, fescue grass growth was limited. The DT plots had especially thick stands of wheat, which is why there was relatively low fescue biomass values and coverage, especially on the composted subplots (Figure 16). The addition of compost increased biomass on the C, ST, and DT plots (Table 8). The addition of compost to the C and the ST plots significantly increased biomass. Since only two DT plots included a compost sub-treatment, not enough data were available for statistical analysis. GIS coverage estimates were made two weeks after the wheat grass was removed, allowing the fescue to receive light. Vegetative coverage estimates show relatively good coverage for all treatments and there were not statistical differences

Figure 16. Plot with mostly fescue (left). Plot overtaken with wheat from straw mulch (right).

Table 9. Biomass measurements, without wheat, at the Mountain site.

Treatment	Surface Biomass	
	April 2011 ($g\ m^{-2}$)	May 2012 GIS estimated coverage %
C	23a	73a
C + compost	38a	88b
ST	25a	81b
ST + compost	42a	82b
DT	17a	80b
DT + compost	20a	82

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

Rooting

Piedmont Site

Visual assessment of roots from each treatment showed short and thick roots extending to only 2.5 to 7.5cm on compacted plots (Figure 17). Grzesiak et al. (2002) found similar root characteristics and shallow rooting depth due to soil compaction. ST and DT plots (Figure 18, Figure 19) had an abundance of finer roots in the upper 15cm; the DT plots showed similar root abundance at the 15-30 cm depth. The ST treatment tended to have less vigorous rooting in the lower section, most likely due to roots encountering the non tilled layer of the profile. Tillage resulted in greater root distribution in the profile, similar to the findings of Varsa et al. (1997).

Figure 17. Roots sampled from compacted plots.

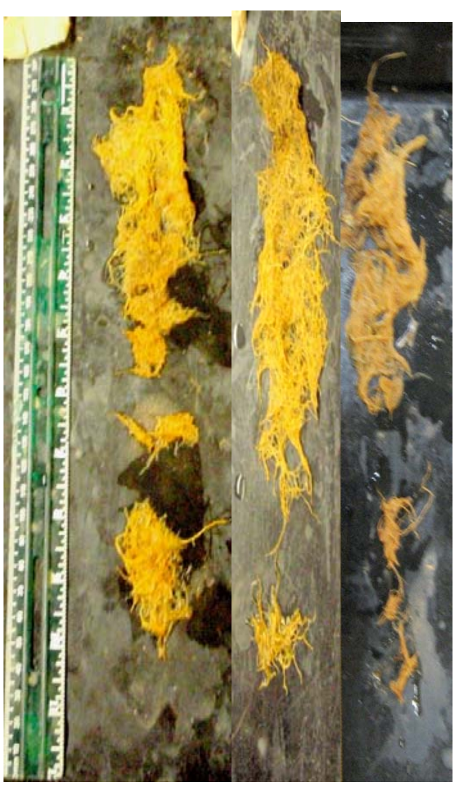

Figure 18. Roots sampled from ST plots.

Figure 19. Roots sampled from DT plots

The root dry weights from each treatment show significantly greater root mass for the DT compared to the controls (Table 10). Deep roots and extensive root systems provide plants with a greater tolerance to water stress (Rowse et al. 1980, Chloupek et al. 2010).The addition of lime within the DT treatment also significantly increased root mass. Lime did not have an effect on root mass for the ST treatment.

Table 10. Dry root weight, Piedmont site.

Treatment	Root Mass (g)
C	0.5a
C + lime	0.3a
S	0.7ac
S + lime	0.6ac
DT	0.6a
DT + lime	1.0bc
DT + 2 lime	1.0bc

‡Means followed by the same letter within a column are not statistically significant.

Sandhills Site

Root profiles extracted from control plots at the Sandhills site demonstrated stresses seen at the Piedmont site; thick and coarse root growth concentrated in the upper few centimeters of the profile (Figure 20). Batey et al. (2004) describes similar distorted thick roots and limited downward growth. The DT treatment always resulted in an even distribution of roots down the profile (Figure 19), while soil cores from ST plots did not consistently demonstrate the same root density at the 15-30 cm depth (Figure 18). Root restrictive soil below the 15 cm till depth most likely contributed to the decrease in roots deeper in the profile. Soil compaction has shown to be one of the main factors contributing to root system development, more so than drought or waterlogged conditions (Grzesiak et al. 2002).

Figure 20. Plants growth on compacted soil concentrated root growth near the surface. Sandhills site.

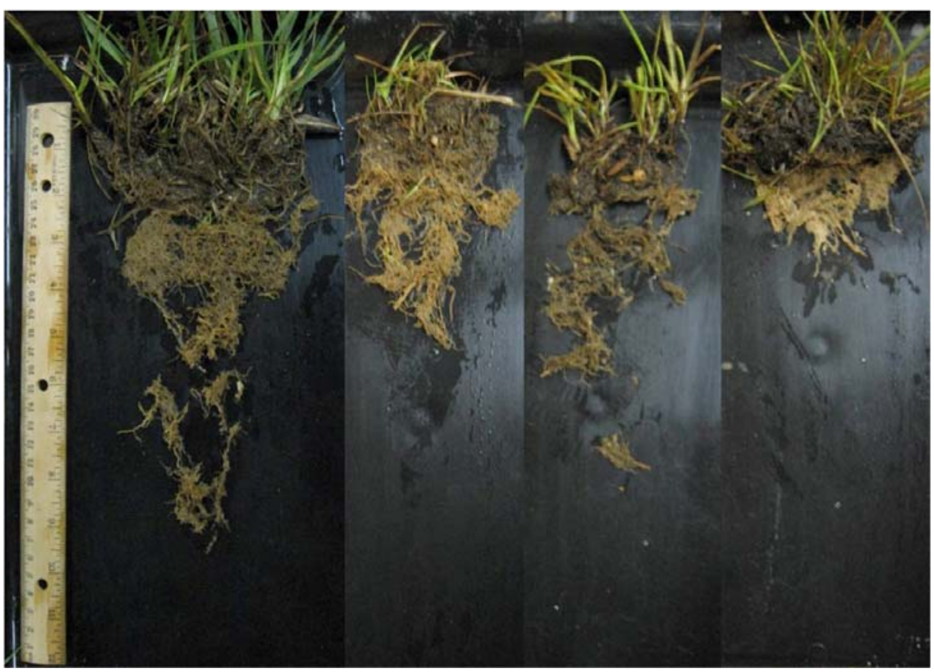

Figure 21. Roots from compacted plots, C + compost (right). Sandhills site.

Figure 22. Roots from ST plots. ST + compost (right). Sandhills site.

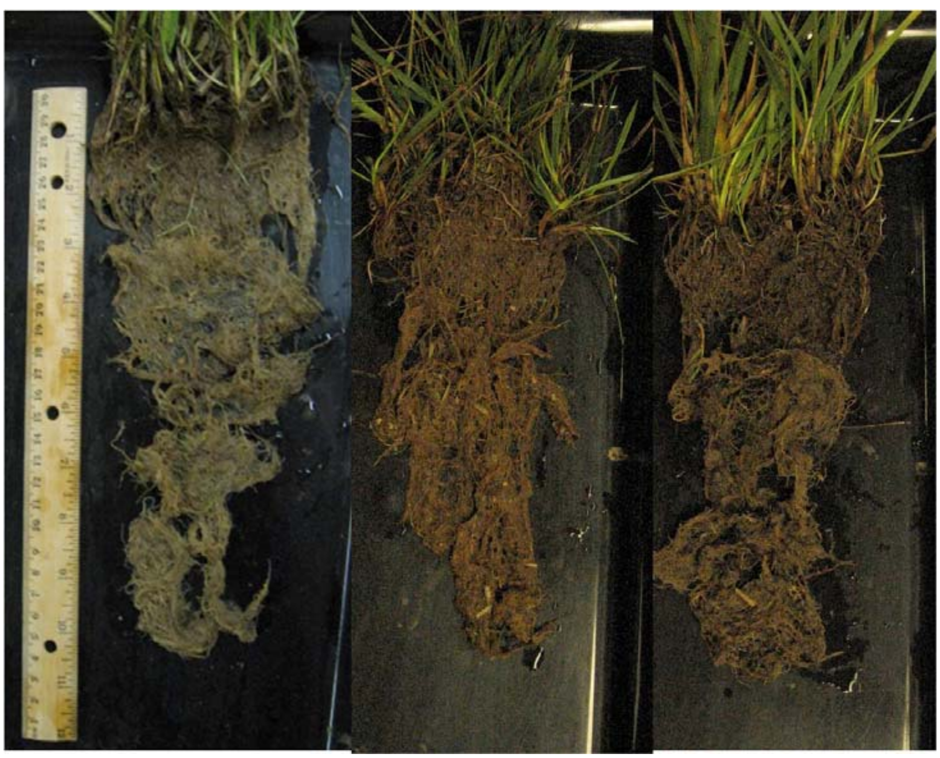

Figure 23. Roots from DT plots, DT + compost (right). Sandhills site.

Mountain Site

Tilled plots tended to have more roots in the 15-30 cm portion of the profile and more fine roots throughout the profile. On most of the C plots, plants were able to extend roots only in the upper 5-10 cm of the profile; these roots also appeared thicker and shorter (Figure 27). A critical point for reduced root growth corresponded to high bulk density and high clay + silt content in a study by Jones (1984). Root photos show less extensive root development compared to similar treatments at the Piedmont site, this could be attributed to sampling in March after the dormant season compared to late spring at the Piedmont site. Soil samples taken from tilled plots showed plant roots growing around soil peds, possibly aiding in the recreation of soil structure after initial tillage (Figure 24). There were not consistent visual differences resulting from compost application.

Figure 24. A network of plant roots encasing soil peds. Mountain site.

Figure 25. Roots sampled from DT plots and DT + compost (right).

Figure 26. Roots sampled from ST (two left) and ST + compost (two right).

Figure 27. Roots sampled from the C and C + compost (right photo).

Infiltration

Infiltration measurements using a Cornell Sprinkle Infiltrometer (CSI) were made at each site. Measured runoff rates varied with the rate of water addition and soil moisture. Values for infiltration are represented as a percent of the irrigation rate from the infiltrometer. The irrigation rate was varied among treatments, with lower rates on control plots due to rapid runoff rates. Infiltration rates generated by the CSI may not be representative of the actual soil infiltration capacity due to high (20-60 cm h^{-1}) rainfall rates. Additionally, the potential lateral flow of infiltrating water below the ring may increase infiltration rate on unsaturated soils (Figure 28). Lateral flow toward drier areas of the soil pulls water from the surface towards areas outside the ring.

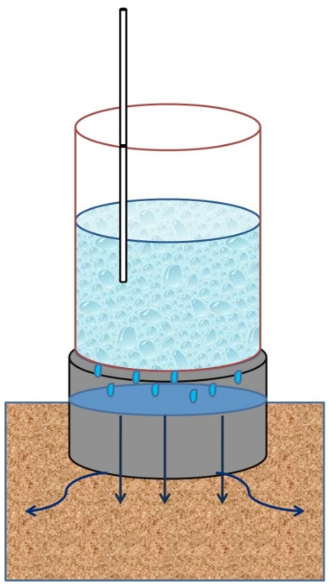

Figure 28. Lateral flow of water can occur with the Cornell Sprinkle Infiltrometer.

Piedmont Site

Infiltration measurements at the Piedmont site were made approximately four months after plot installation to allow for vegetation establishment. The C treatment had significantly lower infiltration rates compared to both the ST and DT treatments (Table 11). An infiltration survey by Yang et al. (2011) found similarly low infiltration rates in urban areas, 63 mm hr^{-1} to less than 1 mm hr^{-1}. Other studies have shown poor infiltration due to compaction (Siyal, 2002; Woltemade, 2012). The high infiltration rates measured for the ST and DT treatments exceeded that found by Al-Ghazal (2000). The increase in infiltration from tillage was also documented in a study by Lipiec (2005) that demonstrated tillage increasing infiltration by 61%.

Table 11. Infiltration rates at the Piedmont site, June 2011.

Treatment	Irrigation Rate ($cm\ hr^{-1}$) Irrigation Range	Avg. Irrigation	Infiltration (%) Avg. Infiltration	Avg. Infiltration
C	30 - 42	36	2a	6a
ST	24 - 66	47	31b	72b
DT	24 - 63	43	30b	72b

‡Means followed by the same letter within a column are not statistically significant.

Sandhills Site

Infiltration measurements were taken twice at the Sandhills site, immediately after tilling and four months afterward. The C treatment had very low infiltration rates at 0.4 cm h^{-1} or 1% of irrigation rate (Table 12), surprisingly low given the high sand content (%) of this soil. Conversely, the very low bulk density and sandy soil created conditions for rapid surface infiltration, 38 and 39 cm h^{-1}, for the ST and DT treatments, respectively. The addition of compost did not change the infiltration rates for ST and DT treatments (data not shown). The tilled treatments had greater than 95% infiltration at irrigation rates up to 50 cm h^{-1}.

After four months, decreased infiltration rate was seen on the ST plots from 95% to 80% of irrigation rates, though not statistically significant, probably due to the increase in bulk density over time (Table 5). Infiltration increased on control plots, from 1% to over 10%, likely due to grass roots loosening the soil surface, allowing water to enter the profile at the surface. There was a corresponding significant decrease in the surface (0-15cm) bulk density from August to January on control plots. Compost did not affect infiltration rate for any treatment.

Table 12.Infiltration rates at the Sandhills site, August 2011 and January 2012.

	Irrigation (cm hr^{-1})		**Infiltration (%)**	
Treatment	**Range**	**Avg.**	**Aug. 2011**	**Jan. 2011**
C	20 - 40	31	1a	10a
C + compost	20 - 38	30	.7a	9a
ST	30 - 50	40	95b	81.5b
DT	30 - 50	40	98b	100b
ST + compost	30 - 45	39	97b	80.5b
DT + compost	33 - 52	41	100b	100b

‡Means followed by the same letter within a column are not statistically significant.

Mountain Site

As was found at the other sites, the compaction treatment resulted in very low infiltration rates, with an average rate of 0.5 cm h^{-1} or 2% of the irrigation rate (Table 13). Ponding of water on the soil surface occurred at even low irrigation rates (Figure 29), indicating that during a storm event nuch of the rain would run off under similar compaction. Infiltration percent increased to 88% and 95% compared to the control for ST and DT treatments, respectively. Infiltration measurements were made on freshly tilled soil, the rate may decrease on the tilled treatments as the soil loses porosity due to settling and traffic, as occurred at the Sandhills site.

Figure 29. Ponding on the surface of a control plot.

Table 13. Infiltration Rates at the Mountain site, October 2011.

	Irrigation (cm hr^{-1})		Infiltration	
Treatment	**Range**	**Avg.**	**Avg. (cm hr^{-1})**	**%**
C	19 - 30	24	0.5a	2a
ST	33 - 90	53	48b	90b
DT	32 - 77	53	51b	97b

‡Means followed by the same letter within a column are not statistically significant.

CONCLUSION

Soils left compacted after the construction phase have limited infiltration and increase the surface runoff rates during storm events. The results of the experiments conducted at three sites suggest that tillage is a viable technique for improving water infiltration on compacted subsoil. The 15 and 30 cm tillage depth infiltration rates were not different, but the deeper tillage resulted in more root growth below 15cm. Tillage mechanically breaks up the soil profile, immediately adding porosity for rapid transfer of water through the soil profile. Implementation of this practice could be a practical addition to a comprehensive storm water plan following construction. Additionally, the soil bulk density and penetration resistance was minimally influenced by the introduction of lawn mower traffic. This shows promise for longer term infiltration capacity of a soil. Preliminary measurements using the CSI indicate that infiltration rate was unchanged and remained high on deep tilled soil after traffic from a riding lawn mower.

Large pores also provide air channels for grass roots to extend. Plants had more roots and extended deeper into the profile when the soil was tilled. Post construction soils typically have a massive soil structure with minimal pores and distribution of pore sizes. Well developed root systems could aid in the maintenance of soil structure after tillage. Tillage immediately introduced macro porosity and allowed plants to establish roots to 30 cm depths within a relatively short period of time. Increased drought tolerance would be expected with deep rooted plants. At the Piedmont site, both the ST and DT treatments resulted in greater above ground biomass as well as percent coverage compared to the control. At the Sandhills site, few differences were seen in percent coverage except surface applied compost severely limited grass growth (42% coverage), while incorporated compost on the DT treatment resulted in significantly higher surface grass coverage. Conversely, surface applied compost at the Mountain site significantly improved coverage. This could be attributed to cooler and wetter growing conditions, preventing the compost layer from drying out and inhibiting seed germination. Permanent vegetative ground cover is the most effective measure preventing soil loss. The biomass results from the Sandhills and Mountain sites were inconclusive. Weed competition at the Mountain site contributed to low biomass values and poor growth overall at the Sandhills site may have been due to water stress attributed to excessively drained soils. There may be value amending subsoil with organic material. Although the advantages were not consistent, compost may provide more long term benefits, which were beyond the scope of this study. Composted plots at the mountain site had stronger grass stands initially, although this visual difference was not evident later on in the season. Thicker A horizons were common on soils with high infiltration rates using the CSI on native sites. Incorporation of organic material into the surface of a subsoil may mimic the high infiltrating properties of an A horizon. Additionally, the breakdown of organic material by organisms within the profile over time may provide additional pore space.

Although most subsoils in this region are acidic, the areas used for testing had been farmed and limed in the past. Soil test results indicated low liming rates (pH 5.7 in the Piedmont, pH of 6 at the Sandhills and Mountain sites) and this was the primary reason why no significant differences were seen from lime application. The cross-linked polymer applied at the Mountain site was not included as a treatment during data collection. The large tillage equipment made incorporating the granular polymer into a small area difficult. All plots with this treatment may not have had even polymer application to make sound comparisons. Polymer additions may be useful on soils where moisture limits grass growth;

the Mountain site received adequate rainfall and there was no evidence of water stressed vegetation.

CHAPTER 3: PIEDMONT SITE STORM EVENTS

Simulated rainfall experiments provide solid data for relating treatments within a study, however, they are not always representative of field conditions. A total of twelve rainstorm events were captured at the Piedmont site; total runoff and water quality measurements were made. Lindstrom et al. (2001) reviewed soil erosion in terms of tillage and landscape hydrology. Tilled soil is vulnerable to erosion before vegetation becomes established. Relationships between soil erosion and rainfall have been extensively studied under simulated conditions and have shown that intensity influences the type of sediment lost (Jennings et. al 1987, Parsons et al. 2006, McIsaac et al. 1992). It is well known that sediment delivered to streams via storm runoff negatively affects aquatic systems (Marshall et al 2010, Mol et al. 2003).This portion of the study aimed to quantify erosion and determine water quality impacts from tillage practices implemented to enhance storm water infiltration.

MATERIALS AND METHODS

Storm Runoff collection

In order to collect storm water, a 1.2 m x 1.2 m square was delineated at the end of all 28 treatment plots using 10cm high plastic garden edging pounded into the soil several centimeters. The edges and gaps were sealed with expanding foam insulator (Great Stuff, Dow Chemical Company, Wilmington, IL). Along the lower end, an opening was left and a 5 cm 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 of the plot area. Assuming 100% runoff, the tub size allowed us to capture all runoff from a 0.5 year 24 hour storm in Piedmont N.C., which is 36.6 mm (NOAA Atlas 14).To minimize precipitation from diluting runoff samples, each tub was fitted with a lid, into which a 10 cm diameter hole was drilled out for the pipe to enter.

Subsamples of storm runoff from collection tubs at the Piedmont site were analyzed for turbidity, total suspended solids (TSS), and nutrients (storms 1-5 only). An onsite rain gauge was used to measure total rainfall and corresponding hourly data was collected from the NC Climate Office (State, 2009). After each storm event, runoff volume was determined by recording the depth of water within the pre-calibrated collection tub. Water within the tub was then mixed thoroughly, to suspend sediments, while a sample was taken. If runoff was minimal, less than one liter, the entire sample was taken. Turbidity values were determined using an ANALITE NEP-160 turbidity meter. Each sample was shaken for 10 seconds and values read 20 seconds later. Turbidity measurements were corrected based on a standardized curve using formazine. TSS was determined by filtration (Clesceri et al., 1998) using 90 mm glass fiber ProWeigh filters from Environmental Express (Mt. Pleasant, SC). Equation 2 was used to calculate sediment loss.

Equation 2

Sediment loss (kg ha^{1-}) = runoff volume (L) * TSS (mg L^{1-}) * 10^{-6} ÷ plot area (ha)

RESULTS AND DISCUSSION

Runoff and Water Quality

The compacted plots generated the greatest amount of runoff for all 12 storms with average runoff amounts ranging from 6% to 76.2% of rainfall (Table 14). During storms 3, 5, 6, and 9, some individual compacted plots produced greater than 90% runoff. Based on runoff depth, the ST treatment significantly reduced the amount of runoff compared to the compacted C for 10 storms at p=0.05. The DT plots had significantly lower runoff depths compared to the compacted C, with 96% infiltration or greater for all 12 storms. Some individual DT plots, during most storm events, actually had zero runoff, or 100% infiltration. Additionally, the DT treatment had significantly less runoff compared to ST plots for storms 3, 4, and 5 at p=0.01.

Table 14.Percent runoff from 12 storms (March-June 2001) at the Piedmont site.

Treatment	**Storm**											
	1	2	3	4	5	6	7	8	9	10	11	12
	Date											
	3/6	3/9	3/26	4/5	5/9	4/16	4/28	5/4	5/14	5/31	6/20	6/27
	Precipitation (mm)											
	22	14	9	11	33	16	13	12	19	30	15	51
	Runoff Percent											
C	22 a	8a	32a	26a	76a	61a	19a	6a	57a	26a	6a	40a
ST	0.6b	2b	17a	5a	13b	6b	3b	2ab	9b	6ab	2ab	13b
DT	1b	0.6b	2b	1b	2c	3b	2b	1b	4b	3b	2b	3c

‡Means followed by the same letter within a column are not statistically significant at p=0.05.

The relationship between rainfall amount, storm duration and intensity were not always clear. Consistent differenced in runoff from varying storm intensity were not see by Parsons et al. (2006). Conversely, Flanagan et al. (1987) demonstrated storm pattern and time of peak intensity significantly influencing runoff volume, with greater volume for storms with peak intensities occurring later in the storm. Time between storms and vegetative differences may have contributed to varying infiltration among storms in addition to antecedent soil moisture. Cumulative storm runoff over the course of twelve storms shows the C treatment having well over ten times the runoff volume compared to the DT and over six times the runoff compared to the ST treatment (Figure 30).

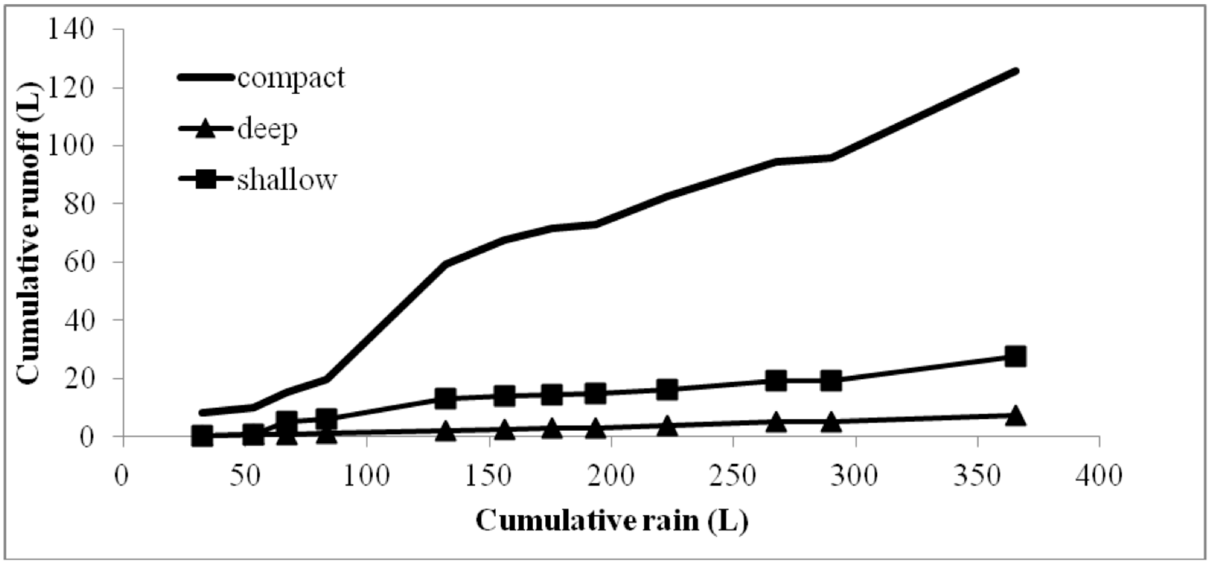

Figure 30. Cumulative runoff over 12 storms. Piedmont site.

Storm runoff amounts in this study seem to correspond to total rainfall and peak intensity as well as peak intensity occurring late in the storm. Storm 5 on 4/9/2011 produced the largest average runoff for the C plots. The total amount of precipitation for storm 5 was 32.5 mm and peak intensity of 6.1 mm hr^{-1}, with most of the rainfall occurring over several hours (Figure 31). For that storm, the average runoff amounts for C, ST, and DT plots were 24.8 (76.2%), 4.3 (13.4%), and 0.7mm (2.1%) respectively. Over all storms, runoff from the compacted treatment was significantly greater than the DT treatment ($p<.0001$).

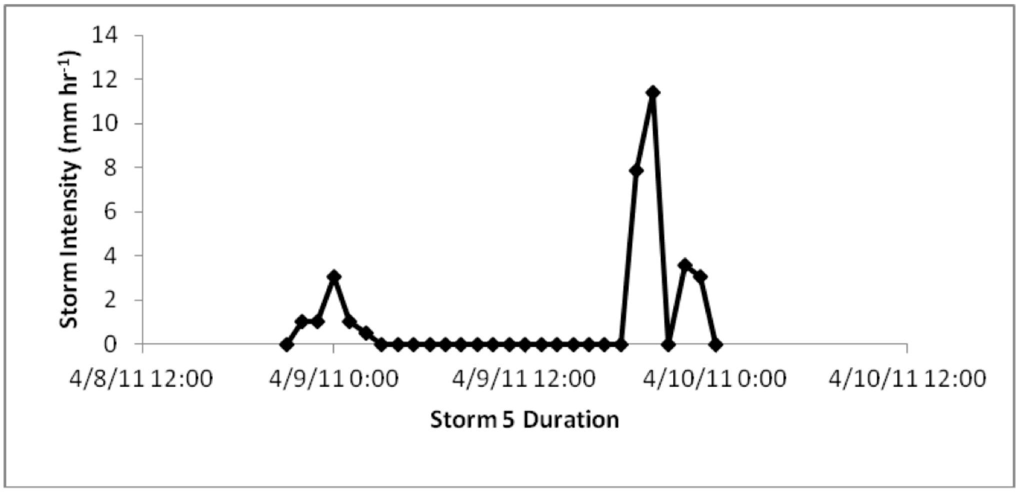

Figure 31. Storm 5 rainfall intensity over the course of the storm

Additionally, the DT plots produced significantly less runoff than the ST ($p= .0065$) for four storms. Storms 6 and 9 resulted in similarly high runoff amounts for compacted plots. Although the total amount of precipitation for storm 6 (Figure 32), on 4/16/2011, was low at only 15.5 mm, it had a peak intensity of 10.9 mm hr^{-1} and the majority of rainfall occurred within three hours. The runoff from C plots averaged 61.1% of the total rainfall. Both ST and DT treatments produced significantly less runoff than the compacted C ($p<.0001$); there were no differences between the ST and DT treatments for this storm.

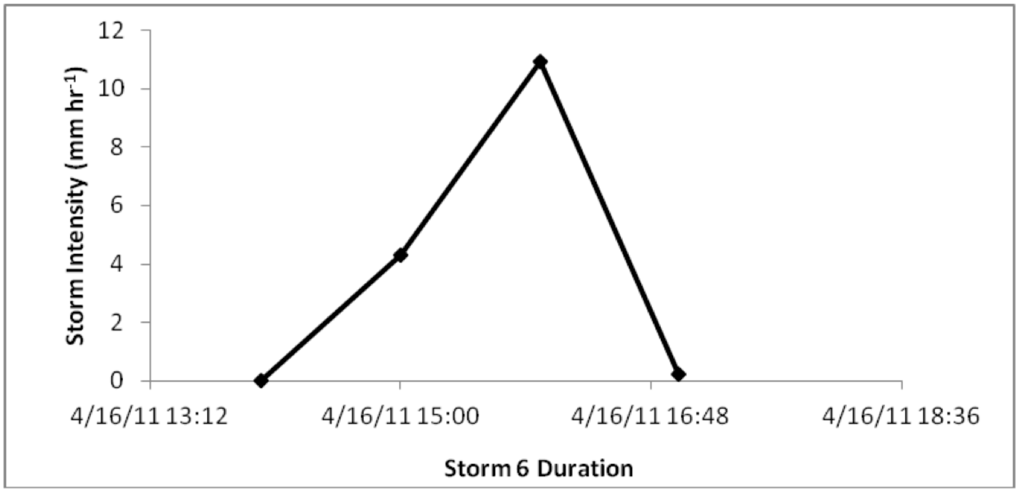

Figure 32. Storm 6 rainfall intensity over the course of the storm.

The storm hydrograph for storm 9 (Figure 33), 16.7 mm hr^{-1}, illustrates a relatively high intensity storm with a single peak, this may have contributed to the high average runoff percent for compacted plots 57.3%. Additionally, the small amount of precipitation at the beginning of the storm may have increased the moisture content of the soil surface, saturating pores and preventing infiltration. Conversely, both ST and DT generated significantly less runoff compared to compacted C plots ($p< .0001$ and $p= .0013$). There were no differences in mean runoff between the ST and DT treatments. The largest storm, storm 12, occurred on 6/27/2011, with 50.8 mm total rainfall and peak intensity of 8.1 mm hr^{-1}. Grass coverage late in the season may have provided some increased infiltration capacity on this larger storm. On C plots, 39.5% of rainfall was collected as runoff, while DT plots had significantly reduced runoff compared to both compacted plots and ST plots ($p=0.004$ and $p=0.01$).

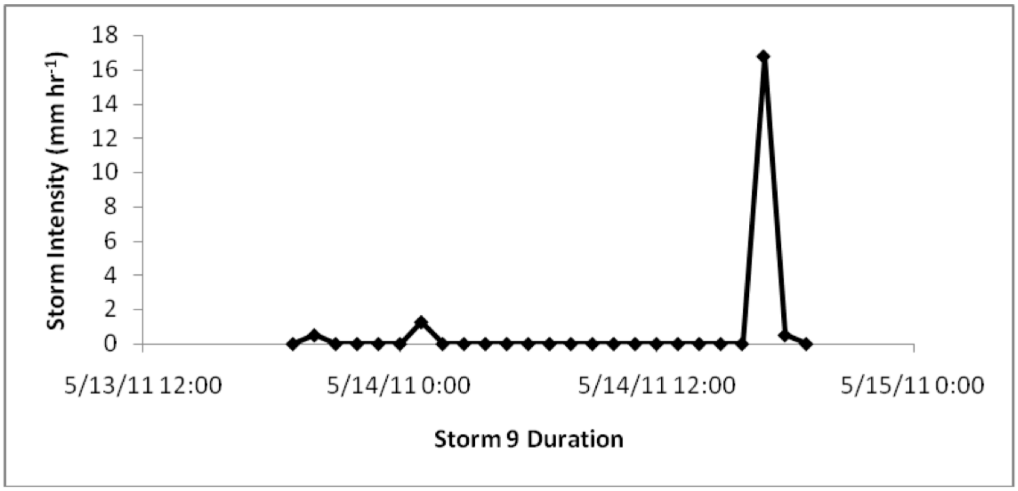

Figure 33. Storm 9 rainfall intensity over the course of the storm.

Storm events with lower runoff volumes tended to have low peak storm intensities, less than 4mm hr^{-1}, low overall precipitation, and long storm duration, generally greater than 12 hours. Storm 8 (Figure 34) was representative of that type with only11.9 mm of total precipitation and a peak intensity of 3.5 mm hr^{-1}, resulting in only 5% runoff even for the compacted treatment. However, for storm 3 (Figure 35) on 3/26/2011,the C plots averaged 32% runoff despite a low total precipitation of 11.2 mm and peak intensity of only 2.0 mm hr^{-1}. Sparse vegetative cover early in the growing season can be attributed to higher runoff rates. Lack of vegetation may also correspond to higher runoff on ST plots as well, with 17% of rainfall running off. For this storm, runoff volume for the DT treatments was still significantly less than both C and ST treatments ($p<.0001$).

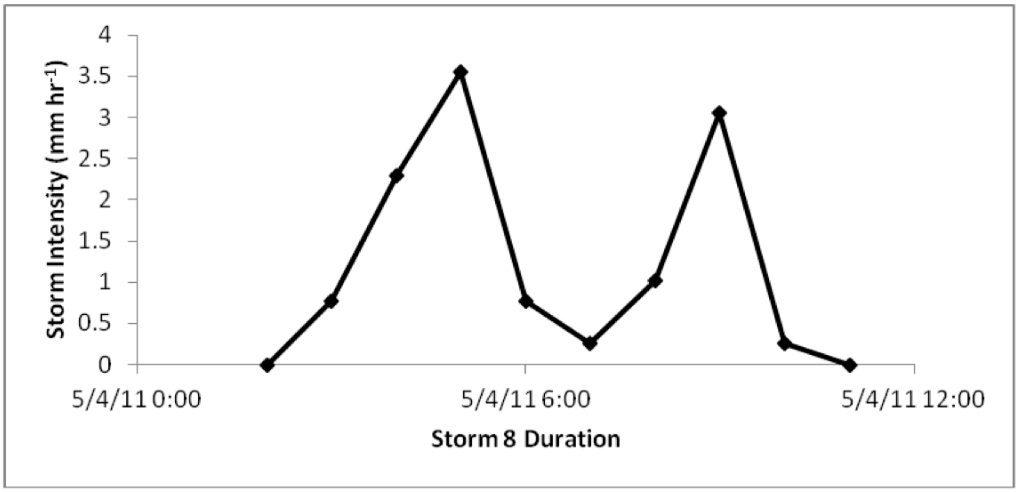

Figure 34. Storm 8 rainfall intensity over the course of the storm.

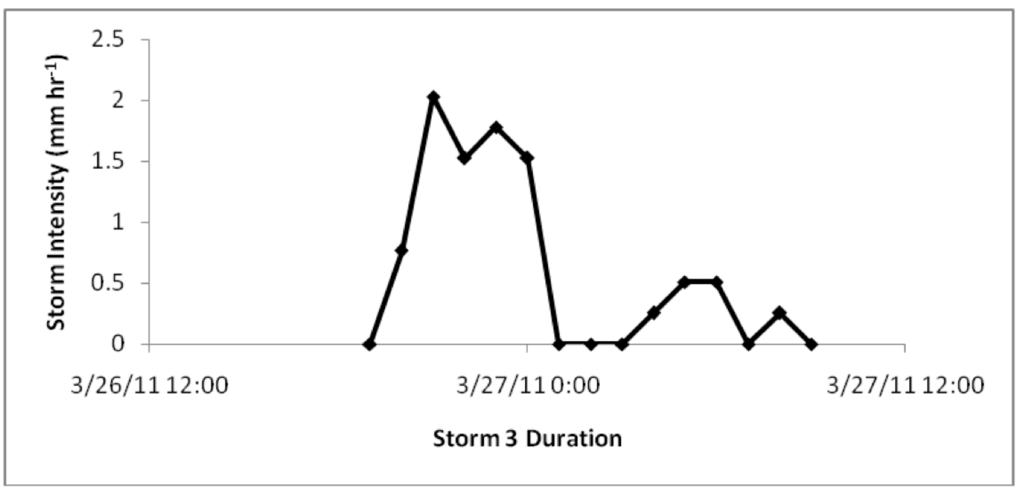

Figure 35. Storm 3 rainfall intensity over the course of the storm.

Turbidity

Trends in turbidity among the three treatments over twelve storms were not consistent and do not correspond well to either precipitation amount or storm date (Figure 36). The C treatment had lower mean NTU for about half of the storms. High variability and standard deviation for all treatments provided few significant differences.

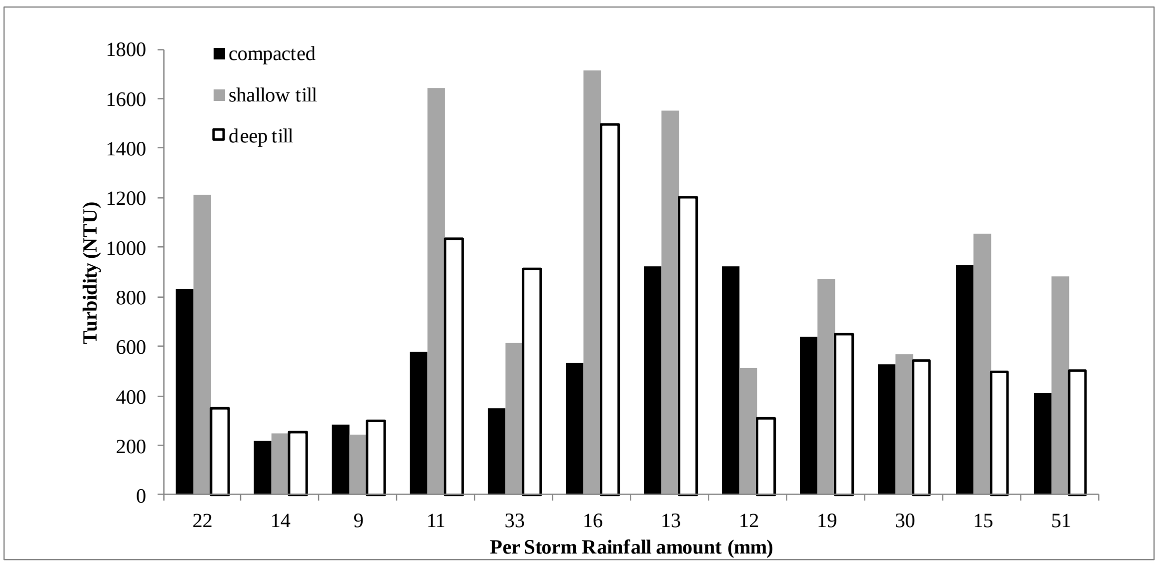

Figure 36. Turbidity measurements for 12 storm events at the Piedmont site.

Sediment Loss

The relationships between soil erosion and rainfall have been extensively studied under simulated conditions and have shown that intensity influences the type of sediment lost (Jennings et. al 1987, Parsons et al. 2006, McIsaac et al. 1992). Excess sediment delivered to streams via storm runoff negatively affects aquatic systems (Marshall et al 2010, Mol et al. 2003).

The compacted C treatment resulted in greater overall sediment loss than either of the tillage treatments during storm events; however, due to high variability, these differences were only statistically significant for eight of the twelve storms (Table 15). Sediment loss values ranged from 3 to 288 kg ha^{-1} for C plots, 2 to 103 kg ha^{-1} for ST plots, and 1 to 58 kg ha^{-1} for DT. There were no statistical differences between the two tillage treatments, although the DT generally had lower total sediment loss values that ST. Low sediment loss values were found on tilled plots later in the season, most likely due to grass cover protecting the soil surface. However, compacted plots maintained approximately 5 times greater sediment loss compared to both tillage treatments in the last three storms. Higher precipitation corresponded to greater sediment loss for all treatments.

Table 15. Total sediment loss by storm, Piedmont site.

Treatment	Storm											
	1	2	3	4	5	6	7	8	9	10	11	12
	Date											
	3/6	3/9	3/26	4/5	5/9	4/16	4/28	5/4	5/14	5/31	6/20	6/27
	Precip(mm)											
	22	14	9	11	33	16	13	12	19	30	15	51
	Total Sediment loss (kg ha^{-1})											
C	37a	2.7a	134a	16a	158a	71a	25a	14a	89a	94a	40a	288a
ST	46a	1.9ab	5a	21a	57a	31b	31a	10ab	13b	19b	7b	103b
DT	45a	1b	11a	9.5b	53a	16b	14a	6b	14b	19b	10b	26b

‡Means followed by the same letter within a column are not statistically significant at p=0.05.

The DT and ST treatments had much lower cumulative sediment loss compared to the control (Figure 37). The DT had minimal additional soil loss after about 130mm of rainfall. Total sediment loss for the DT was under 200 kg ha^{-1} compared to over 2 and 5 times that for the ST and C, respectively.

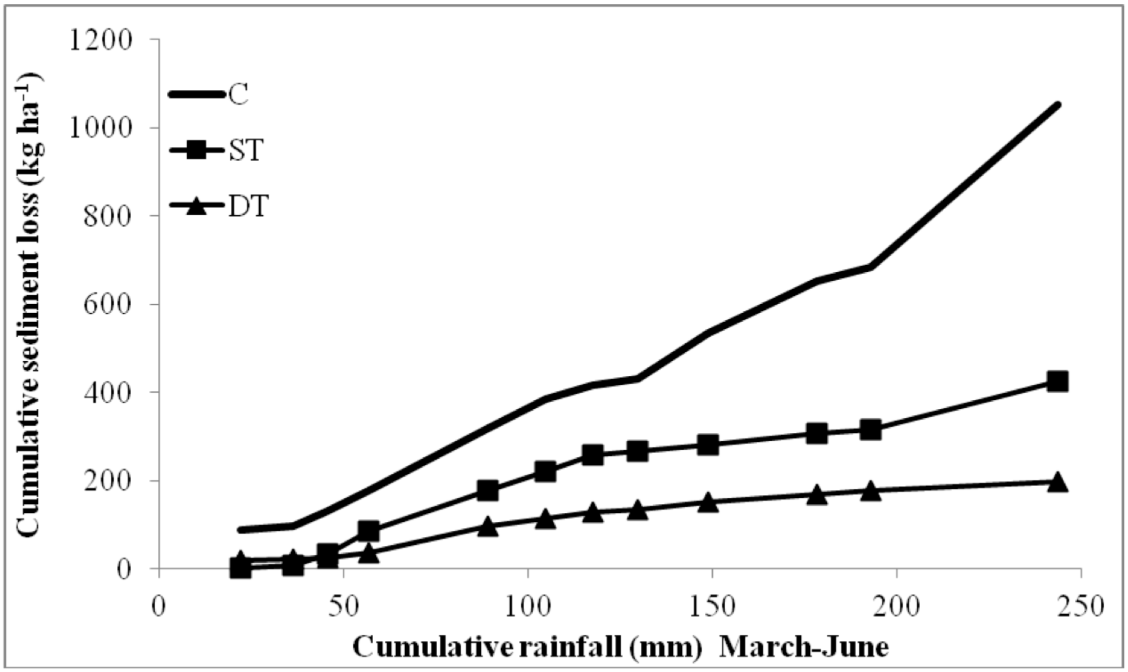

Figure 37. Cumulative sediment loss over 12 storms. Piedmont site.

Deep tillage resulted generated the least amount of runoff and consequently had the greatest storage of water within the profile (Figure 30). The C continued to steadily produce runoff even with vegetative growth.

CONCLUSION

Both deep and shallow tillage treatments reduced runoff during the storm events captured at the Piedmont site. Deep tillage resulted in high infiltration, 96% to near 100%, during all storm events and had significantly less runoff compared to the control plots. High intensity storms over shorter time periods produced greater runoff volumes compared to longer slower storm events. Infiltration at the surface is dependent on the amount of non saturated pores near the soil surface. Additionally, water storage capacity of the soil can be limited by the infiltration rate. The deep tilled plots were able to drain water deeper into the profile, allowing for continued infiltration at the surface. Erosion is a concern when tilling soil. The results from this study indicate that, when implemented on a low slope, tillage did not increase soil loss compared to the control treatment. Additionally, the total sediment loss coming off deep tilled plots was significantly less during seven of the storm events and for five on shallow tilled plots. Soil lost from the surface occurs when water ponds on a saturated soil surface; 12” tilled soil has twice the storage capacity for infiltrating storm water than a 6” tillage depth.

This study explored one way to mitigate urban stormwater control problems. Much of the flash flooding and impaired stream ecology in urban areas can be attributed to runoff from impervious surfaces. Highly compacted surface soils add to the large runoff volumes in urbanized areas, which are often funneled to nearby stream channels. By increasing the water storage capacity through deep tillage, soil may be included as a primary component of a storm water management system. Infiltration into the soil reduces total surface runoff volume and slows water delivery to streams. Using established agricultural techniques, poorly infiltrating compacted subsoils may be remediated to promote strong vegetation and long term infiltration.

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APPENDICES

Appendix 1. Nutrients in runoff, storms 1-5. Piedmont Site.

Storm	**Date**	**Plot type**	**PO4 mg P/L**	**NH4 mg N/L**	**NO3 mg N/L**	**TOC mg C/L**	**TP mg P/L**	**TKN mg N/L**
1	3/1/2011	c	6.10	12.70	< 0.1			
1	3/1/2011	c	10.00	43.20	< 0.1			
1	3/1/2011	d	1.00	2.10	0.21			
1	3/1/2011	d	0.02	0.20	0.29	9.00	1.50	4.60
1	3/1/2011	s	0.05	0.84	< 0.1			
1	3/1/2011	d	0.31	2.10	< 0.1			
1	3/1/2011	d	0.01	0.67	0.37			
1	3/1/2011	s	0.00	1.10	0.33	8.20	2.00	7.70
1	3/1/2011	s	0.01	0.71	0.23			
1	3/1/2011	c	9.00	24.10	< 0.1			
1	3/1/2011	c	0.80	6.70	< 0.1			
1	3/1/2011	s	0.01	0.32	0.21			
1	3/1/2011	s	0.02	0.71	0.34			
1	3/1/2011	spike	0.80	7.30	9.90			
1	3/1/2011	c	6.80	14.20	< 0.1			
1	3/1/2011	c	0.07	0.44	0.27			
1	3/1/2011	c	0.02	0.43	< 0.1			
1	3/1/2011	d	0.02	0.32	2.60			
1	3/1/2011	d	0.03	0.60	0.48			
1	3/1/2011	d	0.01	0.41	3.20			
2	3/7/2011	c	1.90	3.90	0.18			
2	3/7/2011	c	5.40	11.30	< 0.1			
2	3/7/2011	d	0.02	0.74	< 0.1			
2	3/7/2011	d	0.22	2.10	< 0.1			
2	3/7/2011	d	0.02	2.60	1.40			
2	3/7/2011	s	0.00	0.63	0.13			
2	3/7/2011	s	0.03	8.20	1.50			
2	3/7/2011	d	< 0.01	0.82	< 0.1			
2	3/7/2011	d	< 0.01	0.39	< 0.1			
2	3/7/2011	d	< 0.01	0.28	0.21			
2	3/7/2011	s	< 0.01	0.24	0.14			
2	3/7/2011	s	0.01	0.38	0.25			
2	3/7/2011		0.99	10.70	10.50			
2	3/7/2011	c	4.70	5.00	< 0.1			
2	3/7/2011	c	4.60	4.80	< 0.1			
2	3/7/2011	s	0.08	0.85	< 0.1			
2	3/7/2011	s	0.02	0.38	0.11			
2	3/7/2011	d	0.57	3.10	< 0.1	10.90	2.70	20.90
2	3/7/2011	d	0.05	0.86	0.56			
2	3/7/2011	d	1.50	1.60	0.35			
2	3/7/2011	c	1.90	2.80	0.17			

Appendix 1. continued

Storm	Date	Plot type	PO4	NH4	NO3	TOC	TP	TKN
2	3/7/2011	c	3.60	4.70	0.15			
2	3/7/2011	c	< 0.01	0.50	0.17			
2	3/7/2011	c	< 0.01	0.42	0.15			
2	3/7/2011	s	0.03	0.29	< 0.1			
2	3/7/2011	s	< 0.01	0.25	0.14	2.10	0.89	2.80
2	3/7/2011	d	0.02	0.94	< 0.1			
2	3/7/2011	d	< 0.01	0.35	0.23			
3	3/11/2011	c	2.50	7.00	0.56			
3	3/11/2011	c	4.20	12.50	0.43	51.00	4.90	19.00
3	3/11/2011	d	0.05	0.68	0.30			
3	3/11/2011	d	0.75	1.40	0.34			
3	3/11/2011	d	0.13	1.80	1.90			
3	3/11/2011	s	0.06	4.80	1.10			
3	3/11/2011	s	0.01	9.80	2.30			
3	3/11/2011		1.20	19.50	13.00			
3	3/11/2011	d	0.29	1.50	4.00			
3	3/11/2011	d	0.16	0.70	1.40			
3	3/11/2011	d	0.06	0.39	1.20			
3	3/11/2011	s	0.07	0.45	0.45			
3	3/11/2011	s	0.06	0.40	0.98			
3	3/11/2011	c	0.54	1.70	2.80			
3	3/11/2011	c	0.10	3.90	29.70			
3	3/11/2011	s	0.01	0.75	0.34			
3	3/11/2011	s	0.02	0.60	0.22			
3	3/11/2011	d	0.03	0.61	0.49			
3	3/11/2011	d	0.03	0.83	4.20			
3	3/11/2011	d	0.03	0.96	0.37			
3	3/11/2011	c	0.14	1.20	0.96			
3	3/11/2011	c	2.10	4.00	0.63	36.40	2.60	7.80
3	3/11/2011	c	3.70	1.30	0.12			
3	3/11/2011	c	0.07	0.33	0.13			
3	3/11/2011	s	1.50	0.45	0.29			
3	3/11/2011	s	0.28	3.10	1.40			
3	3/11/2011	d	0.06	0.41	0.22			
3	3/11/2011	d	0.16	0.92	2.50			
3	3/11/2011	d	0.24	1.30	2.80			
4	4/1/2011	c	0.79	1.60	0.31			
4	4/1/2011	c	1.30	1.10	0.33			
4	4/1/2011		2.30	10.60	11.30			
4	4/1/2011	d	0.02	0.63	0.49			
4	4/1/2011	d	0.08	0.87	0.46			
4	4/1/2011	d	< 0.01	2.80	18.60			
4	4/1/2011	s	0.27	1.00	3.20			
4	4/1/2011	s	0.02	1.50	0.79			
4	4/1/2011	d	0.85	5.30	2.70			
4	4/1/2011	d	0.02	0.91	11.00	38.60	0.52	6.70
4	4/1/2011	d	0.01	< 0.1	0.43			

Appendix 1. Continued

Storm	**Date**	**Plot type**	**PO4**	**NH4**	**NO3**	**TOC**	**TP**	**TKN**
4	4/1/2011	s	0.03	1.20	9.20			
4	4/1/2011	s	0.01	< 0.1	< 0.1			
4	4/1/2011	c	1.60	1.50	< 0.1			
4	4/1/2011	c	1.70	1.40	1.20			
4	4/1/2011	s	0.09	0.58	0.29			
4	4/1/2011	s	0.03	0.78	1.20			
4	4/1/2011	d	0.02	0.96	0.41	9.00	0.61	5.80
4	4/1/2011	d	0.01	0.34	2.00			
4	4/1/2011	d	4.70	2.50	1.60			
4	4/1/2011	c	0.56	0.57	0.30			
4	4/1/2011	c	0.78	0.98	0.72			
4	4/1/2011	c	2.80	2.00	0.26			
4	4/1/2011	c	2.80	2.00	0.26			
4	4/1/2011	s	1.20	0.49	0.38			
4	4/1/2011	s	0.06	2.50	2.40			
4	4/1/2011	d	3.90	0.98	0.36			
4	4/1/2011	d	0.04	1.90	0.41			
4	4/1/2011	d	0.02	1.60	15.80			
5	4/7/2011	c	0.13	0.89	0.24	34.10	1.80	12.40
5	4/7/2011	c	0.98	0.77	0.31			
5	4/7/2011	d	0.01	0.20	0.15			
5	4/7/2011	d	< 0.01	0.12	0.27			
5	4/7/2011	d	< 0.01	0.22	1.10			
5	4/7/2011	s	0.02	0.82	0.51			
5	4/7/2011	d	< 0.01	0.54	0.54			
5	4/7/2011	d	0.02	1.20	1.70			
5	4/7/2011	d	0.02	0.11	< 0.1			
5	4/7/2011	s	0.02	< 0.1	< 0.1			
5	4/7/2011	c	1.30	0.77	< 0.1			
5	4/7/2011	c	1.60	0.80	0.69			
5	4/7/2011	s	0.01	0.43	0.15			
5	4/7/2011	s	0.02	0.44	0.27			
5	4/7/2011	d	< 0.01	< 0.1	0.30			
5	4/7/2011	d	0.01	0.21	1.50			
5	4/7/2011	d	0.25	0.28	0.22			
5	4/7/2011	c	0.08	< 0.1	< 0.1	32.40	1.20	6.20
5	4/7/2011	c	0.55	0.32	0.25			
5	4/7/2011	c	0.83	0.24	0.17			
5	4/7/2011	spike	1.80	10.30	9.20			
5	4/7/2011	c	0.05	5.60	< 0.1			
5	4/7/2011	s	0.02	0.54	< 0.1			
5	4/7/2011	s	0.02	1.40	1.30			
5	4/7/2011	d	0.93	0.34	< 0.1			
5	4/7/2011	d	0.17	0.20	< 0.1			
5	4/7/2011	d	0.02	1.60	< 0.1			

Appendix 2. Average soil water retention values. Mountain site.

	Soil Water retention				
	Pressure (cm water)				
Treatment	0	50	100	340	500
Till	0.52	0.30	0.28	0.27	0.26
Till + Compost	0.53	0.33	0.32	0.31	0.30
PAM	0.52	0.32	0.30	0.29	0.28
Control	0.56	0.45	0.43	0.40	0.39