

QUANTIFYING DECREASES IN STORMWATER RUNOFF
FROM DEEP TILLING, CHISEL PLOWING, AND
COMPOST-AMENDMENT

by

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Abstract

Development dramatically alters the hydrologic cycle by changing the relative percentage of precipitation that contributes to groundwater recharge, evapotranspiration, and runoff. As land is developed, infiltration tends to decrease and stormwater runoff increases in both rate and volume due to increases in impervious area, soil crusting, and soil compaction. One problem with trying to infiltrate runoff on the remaining permeable land after development is that the soil is often heavily compacted by construction activities, preventing acceptable rates of infiltration. Three practices were evaluated in a field study for their effectiveness in reducing excess runoff volume caused by soil compaction. Twelve plots were installed in the early summer of 2002 on a silty soil that had been compacted to simulate construction activities. The plot treatments each had three replications and included a control with no other practices performed, deep tilling only; chisel plowing and deep tilling; and compost-amendment, chisel plowing; and deep tilling. Runoff volume and the amount of natural precipitation were recorded throughout the growing season.

Regardless of the size of the storm event, the chisel-plowed and deep-tilled treatment and the compost-amended, chisel-plowed, and deep-tilled treatment showed large reductions in runoff volume compared to the control. The chisel-plowed and deep-tilled treatment reduced the volume of runoff by 36 to 53 percent. When compost was added, the reduction in runoff volume increased substantially to 74 to 91 percent. The deep-tilled only treatment was shown to increase runoff in all situations other than the rainfall simulation. The increases in runoff volume ranged from 11 to 64 percent. The chisel-plowed and compost-amended plots also produced more vegetative biomass and visually remained healthier than the other plots during the hot dry summer.

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Introduction

A significant fraction of precipitation infiltrates into the soil in undeveloped areas with natural ground cover, such as forest or meadow. This water is filtered and cooled as it travels underground. Some infiltrated water is subsequently discharged into rivers and streams as base flow, which provides a steady contribution of high quality water to lakes, streams, and rivers. A portion of the infiltrated water descends deeper underground to the water table and recharges aquifers. A part of this groundwater recharge replenishes the supply of underground water that can be extracted for domestic and irrigation use.

Development dramatically alters the hydrologic cycle by changing the relative percentage of precipitation that contributes to groundwater recharge, evapotranspiration, and runoff. As land is developed, infiltration tends to decrease and stormwater runoff increases in both rate and volume due to increases in impervious area, soil crusting, and soil compaction. The decrease in stormwater infiltration, results in decreased recharge of groundwater and eventual loss of base flow in streams and rivers. Increased runoff often causes damage to property by erosion and flooding. Stormwater runoff also entrains debris, sediment, and other contaminants, which it transports to lakes, streams, and wetlands. Common contaminants of stormwater runoff include sediment, nutrients, toxic substances, oxygen-demanding materials, and bacteria, all of which can seriously degrade the quality of receiving waters.

Increased infiltration has been viewed as a solution to help solve surface water problems. Many municipalities are now requiring stormwater control of both peak flow and runoff volume to help offset the potential impacts of unmanaged stormwater runoff. Structural measures have been proposed, but these are expensive and have not proven highly effective for controlling the volume of stormwater runoff (Horner, 1999). If not properly maintained, structural infiltration practices will clog, reducing their effectiveness (Horner, 1999).

To reduce or avoid costly structural measures that treat stormwater “after the fact”, methods need to be developed to increase stormwater infiltration on the remaining permeable land both during and after development. One problem with trying to infiltrate runoff on the remaining permeable land after development is that the soil is often heavily compacted by construction activities, preventing acceptable rates of infiltration. Three practices that are relatively cost effective and appear to have potential to reduce soil compaction and runoff volumes are deep tilling (also called subsoiling), chisel plowing, and compost-amendment. Deep tilling fractures the soil and may reduce the effects of compaction caused by heavy grading during land development. Once compaction is reduced, some infiltration will be restored, thereby reducing runoff volumes and peak flow rates. Chisel plowing is similar to deep tilling, but is performed higher in the soil profile. Whereas deep tilling fractures soil to depths of 90 centimeters or more, chisel plowing breaks up the top 30 centimeters of the soil. Compost is a natural organic material that is produced when microorganisms break down organic residue, such as yard waste. Compost-amendments increase the organic matter and provide more tilth in the

soil, which in turn, restores some of the soil's lost porosity. Once porosity is restored, the soil is better able to store and infiltrate runoff.

Research has shown that the infiltration rate of an urban lawn tends to increase as the lawn ages (Legg et al., 1996). Therefore if soil compaction can be mitigated in the first few years following construction, initial infiltration will increase. This increase in initial infiltration would lead to faster lawn establishment and encourage more rapid root zone development by providing a better environment for root penetration. This research evaluated the effects of deep tilling, chisel plowing, and compost-amendment on runoff compared to no control from test sites with soil compacted by simulated construction activities.

The objectives of this study were:

1. To determine if deep tilling soil after heavy grading from construction activities reduces runoff over the first season following soil compaction.
2. To determine if deep tilling and chisel plowing soil after heavy grading from construction activities reduces runoff over the first season following soil compaction.
3. To determine if incorporating compost along with deep tilling and chisel plowing has any additional significant benefit to increasing stormwater infiltration over the first season following soil compaction.

Literature Review

Many scientists believe that if the pattern of paving and roofing over pervious areas that once contributed to groundwater recharge continues, base flows in streams and rivers will be reduced or eliminated and irrigation and drinking water supplies will be affected (Land and Water, 2002). In fact, these effects can already be seen. According to the Dane County Regional Planning Commission (Dane County RPC, 1999), the Yarhara River at McFarland, Wisconsin has already suffered a greater than 50 percent reduction in base flow due to human activities.

In addition to recharging groundwater and reducing runoff, infiltrating runoff into the soil also has a natural filtration capacity. With no other pretreatment, soil is able to remove significant amounts of stormwater contaminants through chemical and biological filtration, and to a lesser extent, mechanical filtration (Bardin et al., 2001). The capability of individual soils to remove contaminants is a function of the physical and chemical properties of the soil and site conditions. This difference in physical and chemical properties of the soil, in part, explains the differences in removal rates from several monitoring studies, as shown in Table 1.

Table 1. Median pollutant removal (%) by infiltration through soil.

Monitoring Study	Total Nitrogen	Copper	Zinc	Lead
Barraud et al., 1999 (New Soakaway)	NA	NA	54	98
Barraud et al., 1999 (Older Soakaway)	NA	NA	31	NA
Bardin et al., 2001	NA	48	25	59
Center for Watershed Protection, 2000	51	NA	95	NA

**NA means no information was reported.*

Soil compaction from construction activities is a primary reason that runoff rates are higher on developed areas than on undeveloped (or forested, or rural) areas. Soil Compaction can have many adverse impacts. Recent research on the compaction of urban soils has shown that there is a significant increase in the bulk density of soils that have been subjected to grading. In fact, a research study by Randrup (1998) found that mass grading increased the bulk density of the soil by 0.35 g/cm³. Schuler et al. (1986) states that the first pass by heavy machinery causes 70 to 90% of the total soil compaction that the implement is capable of achieving. Soil must have adequate pore space to allow for the transport and storage of air and water. When the bulk density of a soil increases, the amount of pore space decreases. The decrease in pore space reduces the soil's ability to infiltrate and store runoff, impedes root growth, limits nutrient uptake in vegetation, and reduces biological diversity and activity in the soil (Soil Quality Institute, 2000). The soil then more closely resembles an impervious surface rather than a pervious lawn or meadow, especially during large storm events. Schueler (2000) and Wignosta et al. (1994) found that runoff from compacted soils found in lawns of a small-developed residential area contributed 40 to 60% of the total runoff, often generating more runoff than the impervious roofs and roadways. This is very important since 50 to 70% of the land area in residential developments is lawn and assumed to be permeable (Schueler, 2000). Table 2 shows a comparison of undisturbed and common urban soil bulk densities.

Table 2. Bulk density for undisturbed soils and common urban conditions (Schueler, 2000).

Undisturbed Soil or Urban Condition	Bulk Density at Surface (gm/cm ³)
Compost	1.0
Sandy Soil	1.1 to 1.3
Silt Loam Soil	1.2 to 1.5
Clay Soil	1.0 to 1.2
Urban Lawns	1.5 to 1.9
Crushed Stone Parking Lot	1.5 to 2.0
Urban Fill Soils	1.8 to 2.0
Athletic Fields	1.8 to 2.0
Concrete Pavement	2.2
Maximum Density for Root Penetration	1.6

As shown in Table 2, by manipulating the land surface through urban development, it is very easy to compact soil to the root penetration limit of 1.6-g/cm³ and thereby limiting vegetative growth. The effects of soil compaction are especially evident on newly established lawns. Legg et al. (1996) monitored 20 lawns in residential areas with ages between one and 70 years in Madison, Wisconsin. Due to lower organic matter content and higher bulk densities, the lawns between one and three years of age produced significantly larger volumes of runoff than the older lawns.

Compacted soils have lower abilities to transfer oxygen, have very high summer soil temperatures, less nutrient retention, and less biological activity than uncompacted soils (Bethenfalvay and Linderman, 1992; Craul, 1994). When these factors are combined with the excessive amounts water that compacted soils need to grow turf, the costs of maintaining lawns are unnecessarily high (Land and Water, 2002).

Although there has been a great deal of research quantifying decreases of urban soil compaction, there has been much less work on how to reverse the impacts of compaction. In the urban setting, soil compaction is much more complicated than it is in agriculture settings (Soil Quality Institute, 2000). Many obstacles usually exist when attempting to reverse compaction impacts such as perennial vegetation, buildings, utilities, and traffic areas. Another problem with urban soil compaction is that normal tillage practices don't

reach the most compacted layers of soil. Whereas conventional tillage typically reaches 15 to 30 centimeters in depth, urban soil compaction commonly extends far deeper, to depths more than 60 centimeters below the surface (Schuler et al., 1986). Lichter and Lindsay (1994) reported that the greatest amount of compaction was found deeper than 30 centimeters below the soil surface, often where most tillage equipment cannot reach and the effects of frost heaving are limited.

The few studies that have examined reversing soil compaction in urban areas have concentrated on two areas: tillage and soil amendment incorporation. Tillage has been used for thousands of years to break up the top layers of soil to prepare seedbeds for planting. One method of tillage that breaks up the soil without turning it over is chisel plowing. Compared to moldboard plowing, which turns the soil over; chisel plowing has been shown to reduce runoff rates by 20% (Chow et al., 2000). A literature review by Schueler (2000) reported that the best tillage practices could only restore one third of the soil density increased due to compaction. The limited benefits of tillage have also been substantiated in a study by Rolf (1994), where it was reported that specialized soil loosening only decreased the bulk density by 0.05 to 0.15 g/cm³, far less than is needed to reverse compaction. These indicate methods for reducing the effects of soil compaction. However, tillage alone will not return soil to its original condition.

One method that may have the potential to alleviate the effects of soil compaction is amending soil with organic material. The two most popular soil amendments are peat and compost. Peat can be costly, may be less available, and does not supply the nutrients that compost does (Land and Water, 2002.) Therefore, compost is most often the better option. When compost is incorporated into the soil, bulk density can be reduced by as much as 0.35 g/cm³, which would help offset the effects of compaction (Kolsti et al., 1995). In addition to reducing bulk density, Kolsti reported that soils amended with compost reduced the volume of surface runoff by 29 to 50 percent. Depending on the amount and type of compost that was incorporated, reductions in runoff volume will vary, however, many scientists report that every one percent of organic matter in a soil can hold up to 16 liters of plant available water per square meter at 30 centimeters depth (Land and Water, 2002). Furthermore, peak flow rates may be reduced or delayed, protecting property from flooding and channels from eroding (Chollak and Rosenfeld, 1998). Compost also has soil-binding properties that prevent erosion. The humus contained in compost acts as glue which holds soil particles together, making the soil more resistant to erosion and improving the retention of moisture (U.S. Composting Council, 1997).

Compost is also a good source of many plant nutrients including nitrogen, phosphorus, potassium and sulfur. Since compost is relatively stable organic matter, these nutrients are released and made available to plant roots slowly, reducing the amount of nutrients lost through leaching (U.S. Composting Council, 1997). Harrison et al. (1996) reported that turf grown on composted amended soil “greened up” more quickly and reached 100 percent cover faster than non-amended soils. With the turf establishing more quickly

compost-amended lawns produce more biomass, have larger individual grass blades, and deeper roots, resulting in thicker and more healthy looking lawns that are more resistant to compaction (Chollak and Rosenfeld, 1998). The United States Environmental Protection Agency found in several field tests that compost addition with no fertilizer to the topsoil resulted in superior vegetation establishment compared to conventional hydromulch methods using fertilizer (United States EPA, 1997). In fact, in a study conducted at the U.S. Air Force golf course in Colorado Springs, Colorado, course areas that utilized compost used up to 30 percent less water, fertilizer, and pesticides than the rest of the course. The EPA also reports that using compost for turf establishment provided the following benefits (United States EPA, 1997):

- Increases soil nutrient content and water retention in all soil types.
- Reduces or eliminates the need for fertilizer.
- Binds heavy metals and prevents their transport to plants and water resources.
- Absorbs odors and degrades volatile organic compounds.
- Prevents erosion.
- Extends municipal landfill life by diverting organic materials from the waste stream.

In addition to enhancing plant growth and pollution prevention, compost is also beneficial in the control of plant disease. It is theorized that compost is able to control plant disease by providing nutrients for competing beneficial microorganisms, antibiotic production from increased populations of microorganisms, predation by soil organisms, and activating disease resistant genes in plants (United States EPA, 1997). Damaging root-eating nematodes and plant diseases such as pythium and fusarium are especially well suppressed by microorganisms found in compost (U.S. Composting Council, 1997). It is also thought that high temperatures found within decomposing compost destroy other potential pathogens and weed seed (Land and Water, 2002). Alternatives to pesticides called “biopesticides” or “tailored compost” are being developed by adding specific microorganisms to compost and are becoming more popular and are expected to be widely available in the near future (United States EPA, 1997).

Approach

Twelve runoff test plots were installed in the Town of Verona, Dane County, Wisconsin. The plots were located within a pasture that had never been disturbed by cropping and had not had any livestock grazing there for more than ten years. The area chosen was on relatively uniform eight to ten percent slope located at the toe of a glacial end moraine that had never been compacted by machinery. There was also ample space to install all 12 test plots across the slope, eliminating the need to stack plots thereby avoiding runoff problems between plots. The existing cover at the beginning of the study was uncut dense grass and other uncultivated vegetation.

In order to verify that the soil conditions were homogeneous, three soil borings were performed on March 28, 2002 with the help of a Natural Resource Conservation Service soil scientist. The soils were found to be relatively uniform in texture, layering, and composition. The topsoil was a 10YR 3/3 silt loam and made up approximately the first 30 centimeters deep. Below the topsoil was a 10YR 4/4 silty clay loam. At depths greater than 100 centimeters, the silty clay loam showed common redox features, indicating that water was present in this layer for extended periods of time. Stones and rocks, were for the most part, absent in the soil. This soil profile is characteristic of the deep silt deposits that are commonly found on the back slope of the driftless area, not in an end moraine area. One possibility for the formation of this silty deposit is that the glacier created a dam and during the glacier's recession the sediment laden melt water filled in the depression upslope of the dam. One benefit of conducting a compaction study on a silty soil is that it is easily compacted, especially when moist.

The test plot area was graded and compacted to simulate construction activity. A Caterpillar D8 bulldozer was used to complete the grading. The D8 stripped and stockpiled the vegetation, which made up roughly the first 15 centimeters from the surface. Once the vegetation was removed, the remaining 15 centimeters of topsoil was pushed into another stockpile. The silty clay loam subsoil was now exposed and the bulldozer made approximately 20 back and forth passes to compact the soil and simulate construction traffic. Since most of the compaction occurs in the first few passes, it didn't take long for the soil surface to become hardened. After approximately 30 minutes, it was evident that the soil reached a high state of compaction, as the soil was visually no longer compressing as the bulldozer passed. A diversion was constructed up slope of the test plot area to keep off-site runoff from affecting the study. Topsoil was then reapplied over the subsoil in the test area by the bulldozer.

During the multiple passes to compact the soil, prior to re-spreading the topsoil, some fine grading was done to construct a uniform 10 percent slope across the hill. Once compaction was completed, the slope steepness was verified by surveying and the boundaries of the twelve 2.4 meter by 3.7 meter test plots were established. A 1.2 meter alley was constructed between plots to prevent one plot's treatment from affecting other plots and to allow drainage from upslope to pass between the plots. In addition, the alley space made it easier for the chisel plow and deep tilling arm to be raised and lowered during application of the practices without effecting other treatments. A random number generator in MS Excel was used to create the randomized block design. Figure 1 shows the layout and order of the runoff plots.

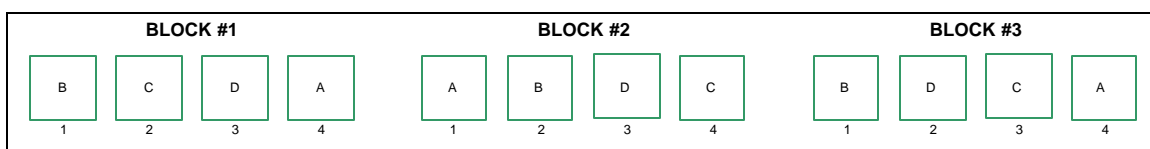


Figure 1. Block and treatment design (treatments are designated by letters).

The letters in the boxes in Figure 1 correspond to the following treatments:

- **Treatment A** - No tillage with seeding and mulching (control site).
- **Treatment B** - Deep-tillage immediately after grading at 1.5 meter spacing and an average depth of 90 centimeters before seeding and mulching.
- **Treatment C** - Deep-tillage immediately after grading at 1.5 meter spacing and an average depth of 90 centimeters followed by chisel plowing with twisted shanks spaced 20 centimeters apart at a depth of 30 centimeters before seeding and mulching.
- **Treatment D** - Deep-tillage immediately after grading at 1.5 meter spacing and an average depth of 90 centimeters followed by chisel plowing with a twisted shank at a depth of 30 centimeters with compost incorporated before seeding and mulching.

Three replications of each treatment were performed in order to account for variability within a given treatment.

The Caterpillar D8 performed the deep tilling treatments. The D8 used a single straight shank deep ripper that was located in the center directly behind the center of the machine (see Figure 2). A single ripper arm configuration was used because it was the only implement available. A two-arm configuration would have been favorable as the arms could then be pulled directly behind the tracks, preventing further compaction from the machine as it travels over the plot. The ripper arm was lowered to its maximum depth of 90 centimeters and pulled through the plots that were to receive deep tilling. Care was taken to ensure that the ripper was raised and lowered within the 1.2 meter alley on each side of the test plots so as not to affect other treatments.



Figure 2. Deep tilling the test plots.

Once deep tilling was completed, chisel plowing was performed on the test plots designated as treatments C and D (see Figure 3). The chisel plow was outfitted with slightly twisted shanks that could achieve a tillage depth of greater than 30 centimeters when drawn by a four-wheel assist tractor. The plow was raised and lowered in the alleys to prevent affecting other treatments. All tillage was completed using the same operator, tractor, and twisted shank chisel plow.



Figure 3. Chisel plow used for treatments.

The final treatment application was applying the compost to the three Treatment D test plots. The compost was obtained from a stockpile maintained by the Dane County Public Works Department and consisted of leaf and brush material collected from residents in the City of Madison. The compost was delivered unscreened and contained many large un-decomposed sticks and foreign objects. In order to create high quality uniform compost the material was screened through a welded wire mesh with five-centimeter openings and all of the stones, sticks, large clods, and other trash items were removed.

The amount of compost added was based on guidance from “Guidelines for Landscaping with Compost-Amended Soils” by Chollak and Rosenfeld (1998). These guidelines state that the optimum organic matter content for soil that is to support turf is between eight and 13 percent by weight. Compost typically contains 45 to 60 percent organic matter and was assumed to provide all of the organics to the soil. Collak and Rosenfeld state that when dealing with loose soil; a ratio of two to one soil to compost should be used and incorporated into the top 15 centimeters of soil. A total of 7.5 centimeters of compost was added to the test plots and was incorporated using a metal rake. The compost was mixed to the extent possible into the top 15 centimeters of soil using a rake. The rake produced similar mixing as would be expected by one pass of a chisel plow. The difference in color between the surrounding native topsoil and the compost-amended soil was dramatic (see Figure 4).



Figure 4. Test plot amended with compost.

A 10-gauge sheet metal diversion border was driven into the ground on three sides of each test plot to control runoff. Runoff from upslope was diverted around the test plot and through the alleys using a cutoff trench. The runoff from the test plots was diverted to dumping bucket gauges through a pvc riser and pipe (see Figure 5). The pipe and riser were designed to not restrict the flow of runoff from a 10-year, 24-hour storm event and assuming a compacted bare surface.

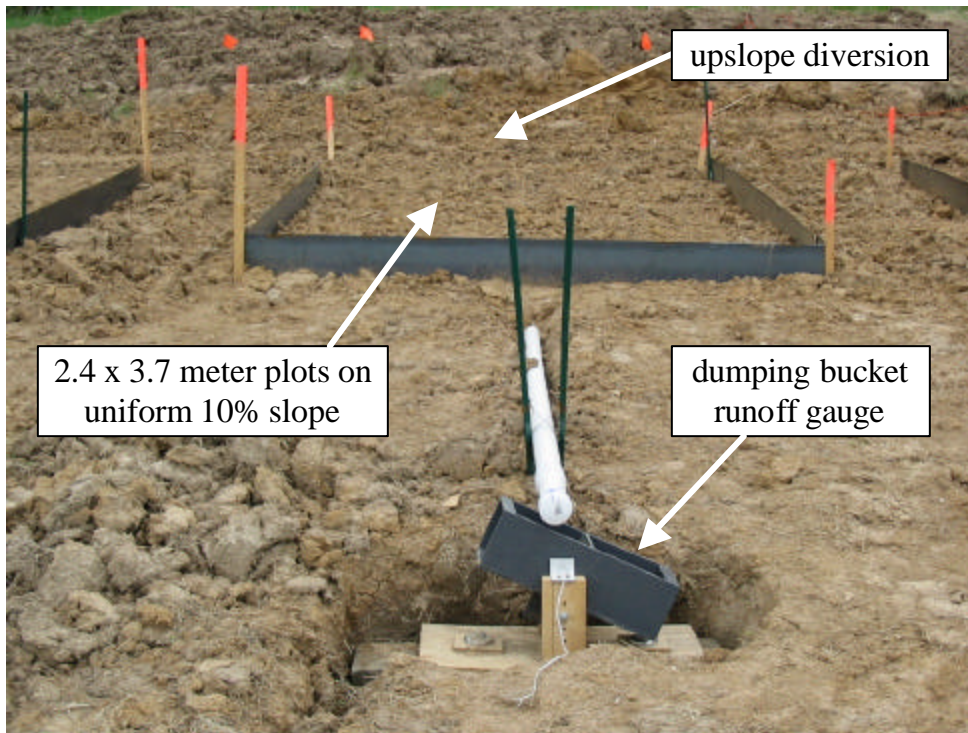


Figure 5. Test plot configuration.

The dumping bucket runoff gauges were constructed of glued pvc and were designed to tip when one side collected between 1.0 and 1.5 liters of runoff. The dumping bucket runoff gauges were rated after installation in the field using a one liter graduated cylinder. Three measurements were taken of the volume of water necessary to tip each side of the gauge. Each gauge's measurements were then averaged to obtain the runoff volume corresponding to a recorded tip. Reed switches connected to Campbell Scientific X21 data loggers were installed on the gauge buckets to record the time of each tip. Each data logger recorded tip information for one block (4 test plots). Channels were excavated below the gauges to allow tipped runoff to drain away freely and not impede gauge operation. A Hobo dumping bucket rainfall gauge was installed in the center of the test plot area to record real-time precipitation rates during the study.



Figure 6. Tipping bucket runoff gauge during tip.

Once the plot borders and gauges were installed, all twelve test plots were seeded and mulched. Prior to seeding, the test plots were rototilled to a depth of 2.5 centimeters. This was necessary as large clods had formed on the surface and seeding would have been very difficult. Seed was then hand applied at a 25 gram per square meter rate over the plots and raked into the surface. Straw mulch was hand spread on all the plots at a 0.3 kilogram per square meter rate. All twelve test plots were installed and operational on June 8, 2002.

Results

During the first 50 days of the study, less than 5.8 centimeters of precipitation occurred at the site. Therefore, a rainfall simulation was performed on July 26, 2002. Five tin cans were randomly placed in each test plot to measure spatial variability of the simulated precipitation. The five measurements were averaged to determine the precipitation depth for each test plot. A hose sprayer was used to apply water to each test plot for 30 minutes and the data loggers recorded the number of gauge tips. Simulated precipitation values ranged from 5.0 to 6.5 centimeters. Table 3 shows the average runoff volume and the percent reduction in runoff for each treatment.

Table 3. Results of simulated rainfall event.

Treatment	Average Runoff Volume (liters)	Average Runoff Depth (cm)	Reduction in Runoff (%)
A - Control	33.9	0.38	---
B - Deep-till	15.2	0.17	54
C - Chisel Plow, Deep-till	11.0	0.12	71
D – Compost, Chisel Plow, Deep-till	0.7	0.01	98

As can be seen from Table 3, drastic reductions in runoff volume occurred for all treatments compared to the control. The treatment utilizing compost (Treatment D) had the greatest reduction in runoff at 98 percent. In fact, the recorded runoff from Treatment D plots was the result of only one gauge on one replication tipping three times. The other two replications of Treatment D produced no runoff, although more than 5 centimeters of precipitation was applied over 30 minutes. For all plots, no runoff was observed until at least 10 minutes into the simulation. One possible reason for this was that the ground was extremely dry and the soil was able to absorb the first portion of the water application. Once the absorption capacity was reached on each plot, runoff was generated. As expected, at a certain time (typically between 15 and 20 minutes) the runoff rates on some of the plots appeared to match the application rate, producing nearly 100 percent runoff during the final minutes.

The deep-tilled only treatments showed a sizable reduction of 54 percent and the deep-tilled and chisel-plowed treatments provide an even greater reduction of 71 percent. This simulation was not used in the analysis of natural precipitation other than to be included as previous precipitation for those storm events.

A statistical analysis of the runoff from all the natural storm event runoff was performed using SAS version 8.0 statistical software. A mixed model was chosen because both fixed and random effects were present in the study. Random effects were assigned to the block level and to the inter-block level using residuals. The fixed effects are shown in Table 4. A mixed procedure was used to handle the 51 missing data points that occurred either due to gauge or data logger failure in the field. The 16 storm events that produced runoff were evaluated with a total of 141 observed data points. The main fixed effects that were tested for significance using a T-test included the treatment, precipitation during the previous week, total precipitation, days into the study, interaction between precipitation the previous week and the treatment, interaction between the total

precipitation and treatment, and the interaction between days into the study and treatment.

When evaluating the residual plot from the original data, a spreading pattern was observed as well as two data points that seemed to be separated from the rest of the data. A statistical analysis showed that these two points were outlying the mean function and they were removed from the data set. In order to correct the spreading pattern on the residual plot a log transformation of the data was carried out. Since the data set contained numerous zero values, the value one had to be added to every volume prior to taking the log value. The residual plot using log-transformed data appeared much more random, but still contained a grouping around the zero values that represented no runoff. The probability values (P-values) were then calculated for the fixed main effects and are recorded in Table 4.

Table 4. T-test for fixed main effects.

Effect	Numerator Df	Denominator Df	F-value	P > F
Treatment	3	121	5.68	0.0011
Week Previous Rain	1	121	0.11	0.7426
Total Precipitation	1	121	64.44	< 0.0001
Days into Study	1	121	1.45	0.2316
Previous Precipitation x Treatment	3	121	1.26	0.2928
Total Precipitation x Treatment	3	121	2.73	0.0470
Days into Study x Treatment	3	121	0.48	0.7000

At the 95 percent confidence level only three effects are shown to be significant: treatment, total precipitation, and the interaction between total precipitation and treatment. All other effects had P-values greater than 0.23. The total amount of precipitation was shown to be highly significant. This significance is not surprising as it was anticipated that runoff would increase as rainfall increased. It was also shown that the effect of plot treatment applied to the plots was significant. No conclusion of which treatments had significantly lower runoff volumes can be drawn from this analysis, however, the overall effect of the different treatments was shown to be important. The significant interaction between total precipitation and treatment was expected as the

different treatments had different amounts of storage and infiltration capacities. As more precipitation continued to fall, the capacities were reached, and runoff matched the precipitation rate.

As the study progressed, the amount of vegetative cover on each plot increased. A drastic and rapid increase in the amount of cover on the compost-amended plots was observed. As can be seen in Figure 7, after only 53 days the deep-tilled and control plots had begun to suffer vegetation burn out due to lack of precipitation and summer heat. The chisel-plowed and compost-amended plots remained green and continued to grow. In fact, the compost-amended plots appeared to remain healthy and vigorous throughout the study, regardless of temperature and precipitation. Percent vegetative cover was also originally tested as a main fixed effect, but was found to be insignificant. No trends between runoff volume and percent cover were observed in the study.

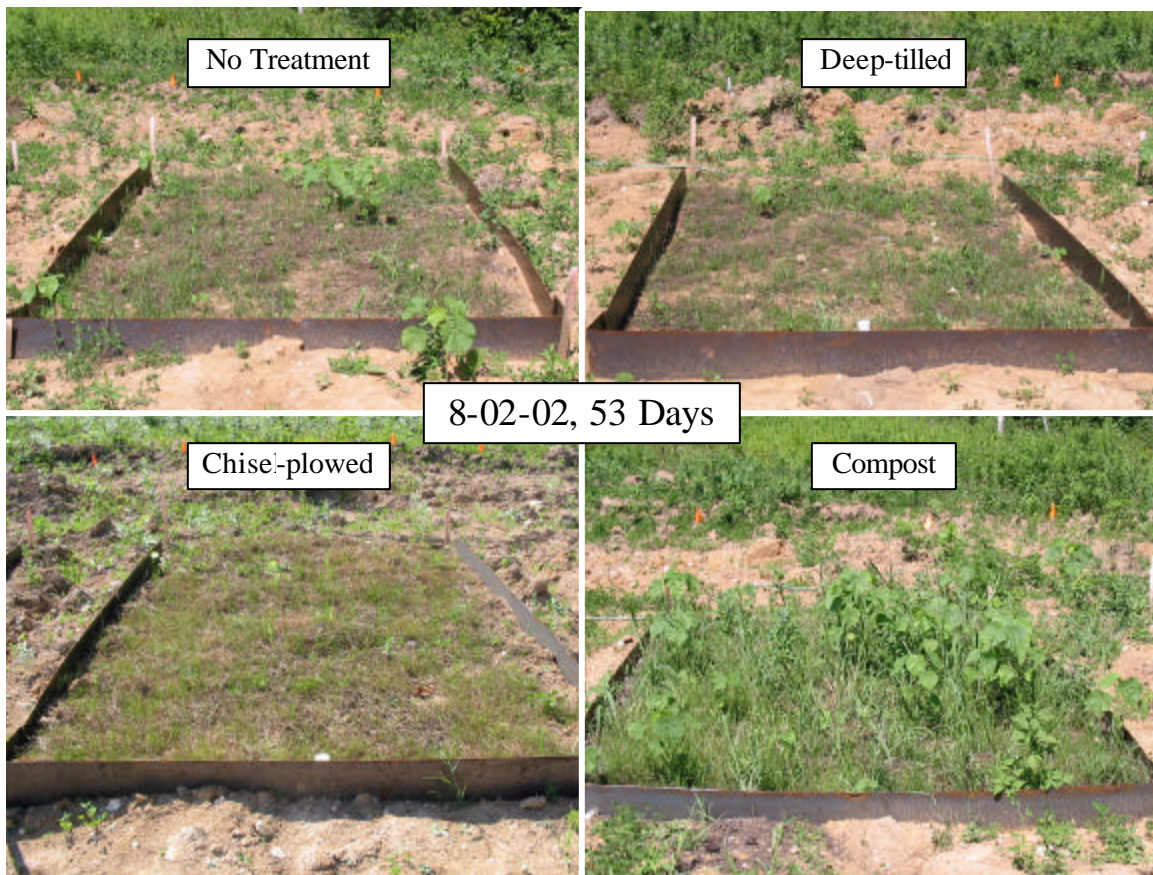


Figure 7. Comparison of vegetation at 53 days.

In order to evaluate which plot treatments significantly reduced runoff volume, pair wise comparisons were calculated using a Tukey-Kramer adjustment on P-value. The results of the comparisons can be seen in Table 5.

Table 5. Pair wise comparison of least square means.

Comparison	Estimate	Standard Error	Df	T-value	P > t	Adjusted P
A to B	-0.2785	0.2068	121	-1.35	0.1805	0.5350
A to C	0.1580	0.2054	121	0.77	0.4433	0.8682
A to D	0.5607	0.2054	121	2.73	0.0073	0.0362
B to C	0.4366	0.2001	121	2.18	0.0310	0.1341
B to D	0.8393	0.2001	121	4.19	< 0.0001	0.0003
C to D	0.4027	0.1986	121	2.03	0.0448	0.1837

At the 95 percent confidence level only the compost-amended, chisel-plowed, and deep-tilled treatment (Treatment D) was show to be significant compared to the control (Treatment A). There is also a significant difference between the deep-tilled treatment (Treatment B) and Treatment D. This is due to the overall poor performance of Treatment B. Treatment B plots produced more runoff over the study period than the control plots. Figure 8 shows the cumulative runoff volumes by treatment. One possibility for the increased runoff volume for the deep-tilled treatments is that a one-ripper arm configuration was used. The one-ripper arm was located between the tracks in the center on the back of the bulldozer, allowing the tracks to create more compaction. If a two-arm configuration had been used, the arms could have been positioned directly behind each track, so that as the tracks compact the soil, the rippers would break it up. As was previously mentioned, when the treatments were applied the soil was at a high state of compaction, so the additional compaction may not have been significant, although the force applied to the soil by the bulldozer while pulling the ripper would be greater than just driving over plots.

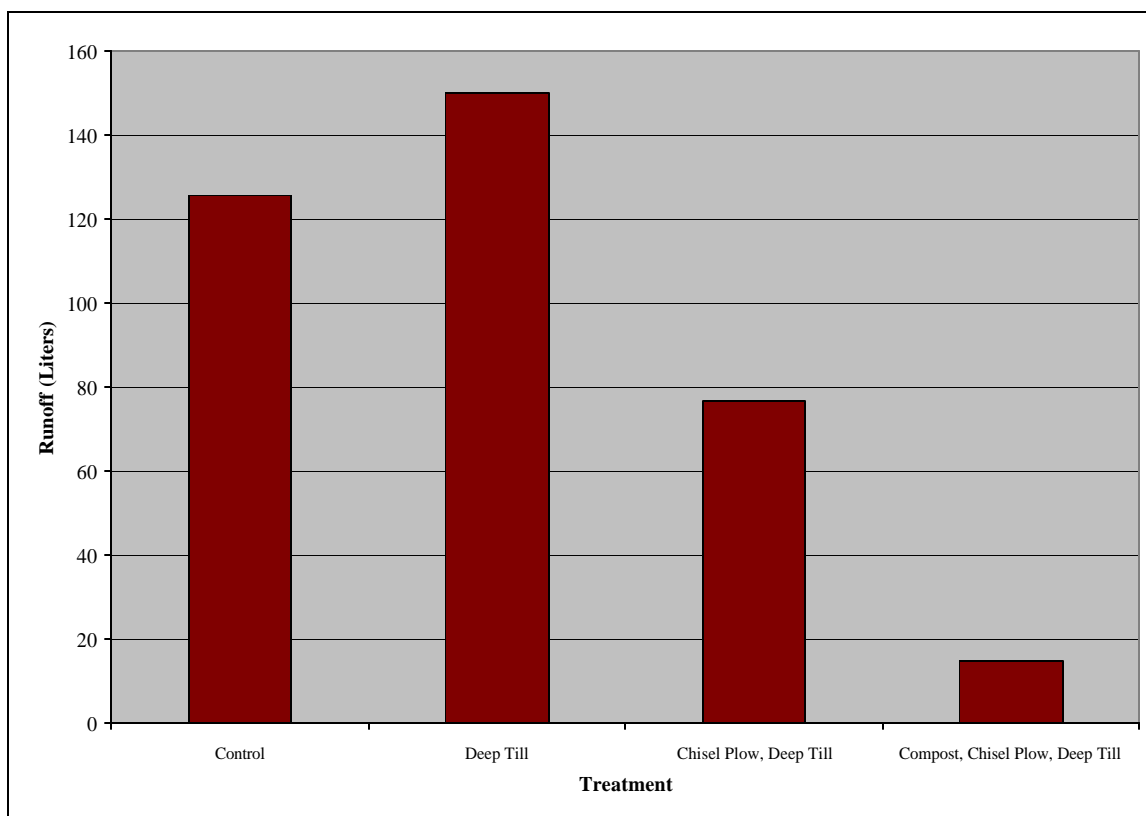


Figure 8. Cumulative runoff through season – all data.

The cumulative runoff volumes shown in Figure 8 are the sum of the average runoff volumes from all three replications of each treatment from all storm events. Where there was missing data from a replication, the average was calculated from the remaining recorded values. The percentage of precipitation that became runoff was quite small. Treatments A, B, C, and D had percent runoff values of 3.5, 4.2, 2.1, and 0.4, respectively.

As can be seen from Figure 8 there is a reduction in runoff volume for two of the treatments. The chisel-plowed and deep-tilled treatment had a reduction in runoff of 39 percent and the compost-amended, chisel-plowed, and deep-tilled treatment had a reduction of 88 percent, compared to the control. The deep-tilled only treatment was shown to actually increase runoff volume by 19 percent, which is consistent with the statistical analysis. The reason that the chisel-plowed and deep-tilled treatment was not shown to be significant in the statistical analysis was due to the large value of standard error. Runoff values tended to be highly variable during the study. By evaluating the overall performance that is shown in Figure 8, the chisel-plowed and deep-tilled treatment does provide a reduction in runoff. The benefit of the two treatments is also evident from the rainfall versus runoff plot for each storm event that is shown in Figure 9. Although the data points are highly variable, the low runoff trends for the chisel-plowed and deep-tilled treatment and the compost, chisel-plowed, and deep-tilled treatment can

be seen. Conversely, the deep-tilled and control treatments show patterns of increased runoff volume as the rainfall volume increases.

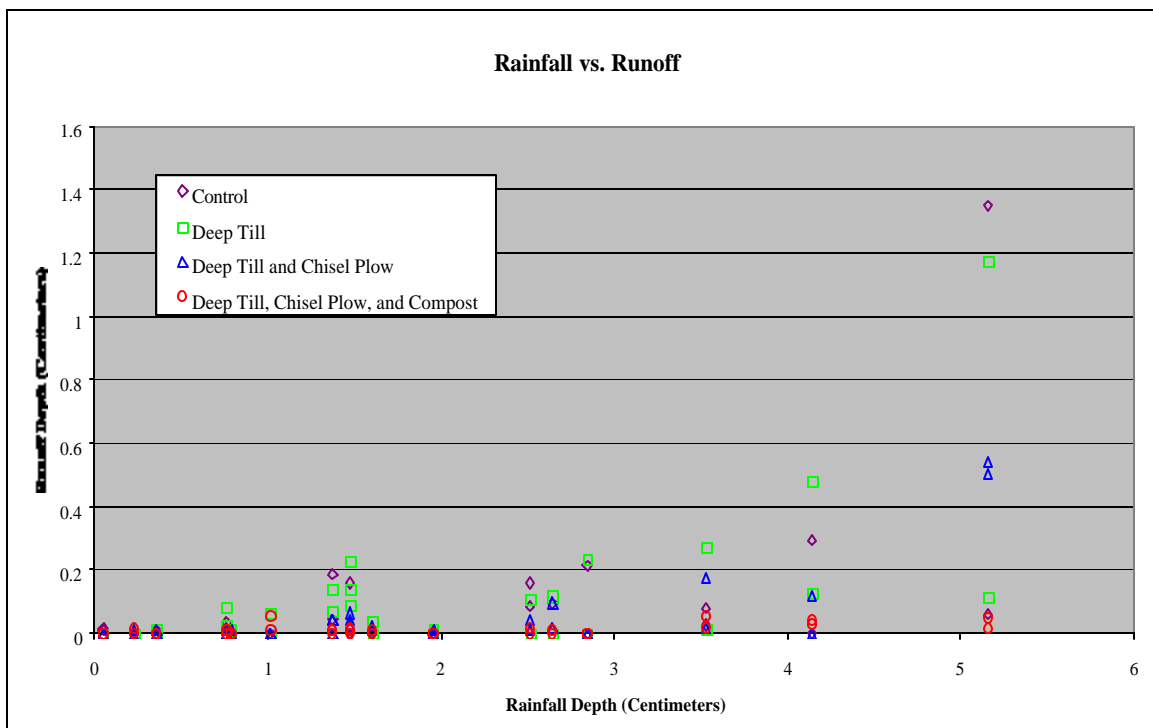


Figure 9. Rainfall versus runoff depth for all data points.

An analysis was also conducted to investigate treatment performance during small and large storm events. It was expected that the differences in runoff reductions would be exaggerated during small storms as the plots may take longer to reach soil storage and infiltration capacities. The test for fixed main effects for storms less 2.50 centimeters is shown in Table 6.

Table 6. T-test for main effects of storms less than 2.50 centimeters.

Effect	Numerator Df	Denominator Df	F-value	P > F
Treatment	3	75	5.15	0.0027
Week Previous Rain	1	75	39.04	< 0.0001
Total Precipitation	1	75	4.41	0.0391
Days into Study	1	75	7.88	0.0064
Previous Precipitation x Treatment	3	75	3.94	0.0115
Total Precipitation x Treatment	3	75	1.27	0.2907
Days into Study x Treatment	3	75	0.93	0.4329

At the 95 percent confidence level, treatment, previous rain, total precipitation, days into study, and the interaction between previous precipitation and treatment were all found to be significant. This test shows that when smaller storms occur, other variables such as the amount of precipitation the week before and the interaction between previous precipitation and treatment, play a much larger role in the amount of runoff generated. Another effect that becomes important is the age of the test plots. As the plots become more established, they are able to absorb and infiltrate more water during small storm events. As with the analysis using all storm data, treatment and total precipitation remain important. When pair wise comparisons between treatments were made, no treatment at the 95 percent confidence level significantly reduced runoff rates compared to the control. The smallest P-value was 0.2337. This is mainly due to the large standard error and smaller degrees of freedom developed from using fewer data points.

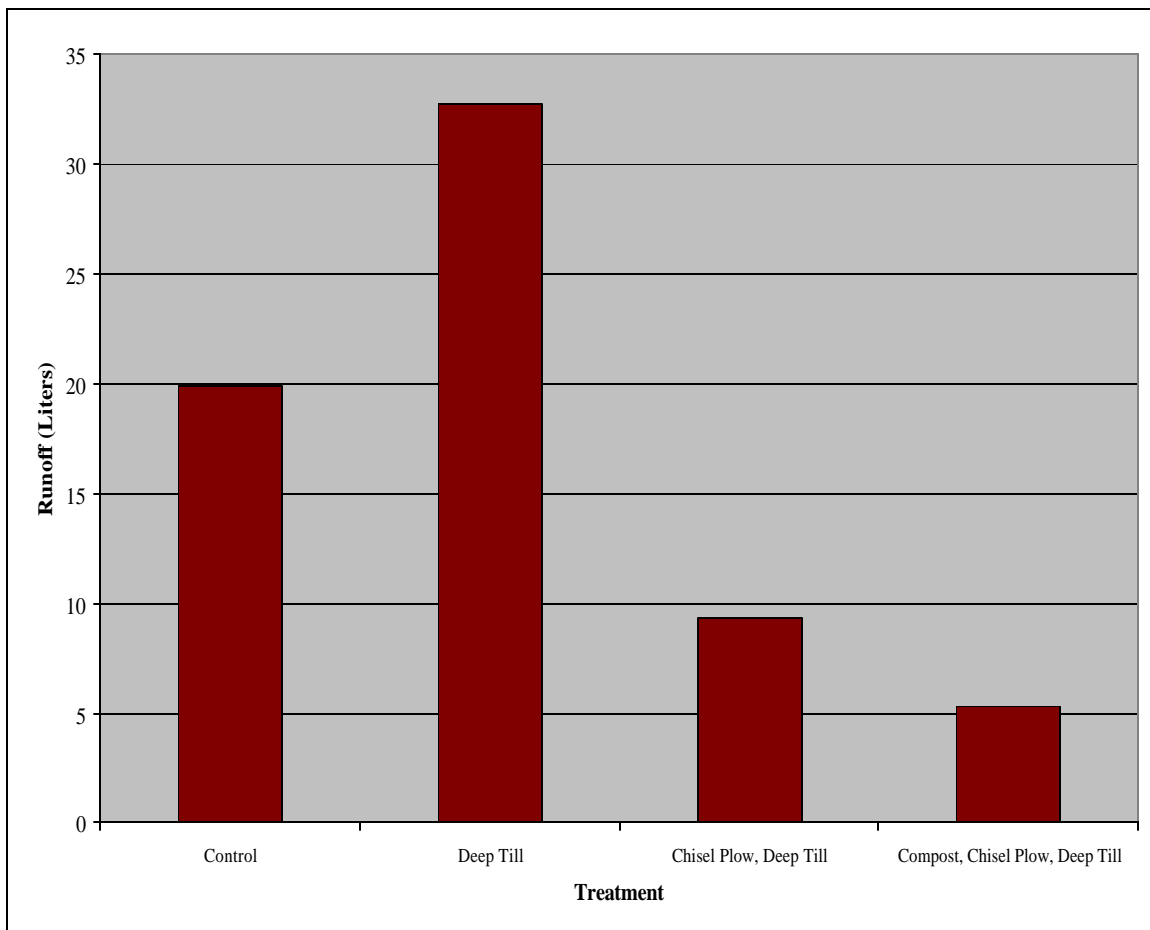


Figure 10. Cumulative runoff for storms less than 2.5 centimeters.

Figure 10 displays the cumulative runoff volumes for the smaller storm events. The values of percent runoff for the small storm events were 1.1, 1.9, 0.5, and 0.3 for treatments A, B, C, and D, respectively. The amount of additional runoff volume with the deep-tilled treatment increased 64 percent, but the benefit between the control plots and the other two treatments remained high. The chisel-plowed and deep-tilled treatment had a runoff reduction of 53 percent and the compost, chisel-plowed, and deep-tilled treatment had a reduction of 74 percent.

Larger storm events (greater than 2.50 centimeters) were also evaluated. The test for significance of the main fixed effects is shown in Table 7.

Table 7. T-test for main effects of storms greater than 2.50 centimeters.

Effect	Numerator Df	Denominator Df	F-value	P > F
Treatment	3	37	1.90	0.1468
Week Previous Rain	1	37	7.97	0.0076
Total Precipitation	1	37	9.14	0.0045
Days into Study	1	37	0.46	0.5033
Previous Precipitation x Treatment	3	37	0.76	0.5250
Total Precipitation x Treatment	3	37	0.97	0.4155
Days into Study x Treatment	3	37	1.30	0.2874

The only effects that are significant at the 95 percent confidence level for large storm events are previous precipitation and total precipitation. During large storm events a larger portion of the rainfall becomes runoff, regardless of the treatment or the age of the plot. Pair wise comparisons of plot treatments to the control plots also showed no significance at the 95 percent confidence level. In fact, the P-values compared to the control treatments were all larger than 0.32.

Figure 11 shows the cumulative runoff volumes for the larger storm events. The percent runoff values for large storm events increased, as expected, to 5.7, 6.3, 3.6, and 0.5 for treatments A, B, C, and D, respectively. The compost-amended treatment still had a large reduction in runoff volume of 91 percent, but the other treatments had much more similar runoff volumes. The runoff volume reduction for the chisel-plowed and deep-tilled treatment was reduced to 36 percent, which is similar to the reduction using all data. The additional runoff volume from the deep-tilled only treatment was reduced to an increase of 11 percent.

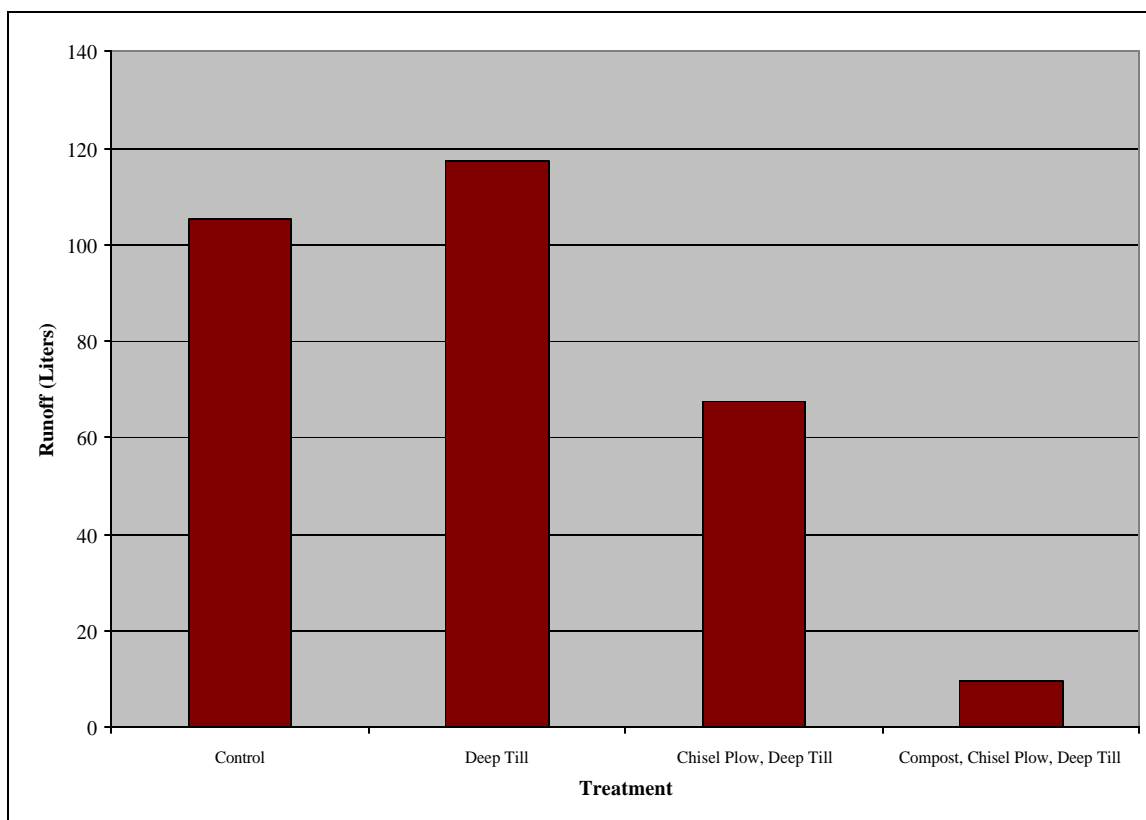


Figure 11. Cumulative runoff for storms larger than 2.5 centimeters.

Regardless of the size of the storm event, the chisel-plowed and deep-tilled treatment and the compost, chisel-plowed, and deep-tilled treatment had large reductions in runoff volume compared to the control. The chisel-plowed and deep-tilled treatments reduced the volume of runoff by 36 to 53 percent compared to the control, and when compost was added, the reduction increased substantially to 74 to 91 percent. The deep-tilled only treatment was shown to increase runoff in all situations other than the simulation. The increases in runoff volume ranged from 11 to 64 percent.

Conclusions

Reduction in soil pore space has been shown to be a primary cause of adverse hydrologic impacts on a watershed (Schueler, 2000). During construction soil compaction is unavoidable as clearing and grading is required to develop the land. In order to reduce soil compaction from occurring on construction sites, it is important to protect undisturbed areas from being used for construction traffic, staging, and material storage, and only manipulate soil when it is dry.

The statistical analysis of all the data concluded that the only treatment that significantly reduced runoff at the 95 percent confidence level was treatment D, the compost-amended, chisel-plowed, and deep-tilled plot treatment. The cumulative runoff analyses of all storm data, small storm data, and large storm data also confirmed the benefit of treatment

D by showing runoff reductions from 74 to 91 percent, compared to the control. Although the statistical analysis did not indicate treatments B and C to be significant in terms of runoff reduction (mostly due to the large amount of standard error that occurred), the chisel-plowed and deep-tilled treatment showed cumulative runoff reductions over the season of 40 to 53 percent, compared to the control. One unexpected result that was common between the statistical analysis and cumulative runoff analysis was the performance of the deep-tilled only plots. The deep-tilled only plots actually had increased runoff volumes between 11 and 64 percent.

Effects that were shown to be significant over the entire study period were the type of treatment and the amount of precipitation. This was expected and provided some assurance that the individual treatments were affecting runoff rates. When only smaller storms were examined, many more effects became important. In addition to treatment and total rainfall, the effects of precipitation the previous week and days into the study were shown to be significant. For larger storms, treatments became less important and the amounts of previous and current rainfall were significant.

A large difference in the amount of aboveground vegetative biomass was observed among the treatments. The vegetation on the control, deep-tilled, and chisel-plowed and deep-tilled treatments suffered during the hot summer months without much precipitation. Once the grass emerged, most of it began to die. On the other hand, the compost-amended plots flourished. This difference in aboveground biomass, however, did not significantly affect the volume of runoff between plots when analyzed statistically. Even though runoff may not have been reduced, the rapid vegetative cover most likely reduced the amount of erosion on the plots by absorbing raindrop impact.

Recommendations

Proper infiltration of stormwater has many benefits in addition to being the only stormwater practice that controls the volume of stormwater runoff once it has been generated. If the volume of water that originally infiltrated into the soil is restored, problems with contaminated runoff, flooding, and erosion may be reduced.

Deep tilling, chisel plowing, and compost-amendment are important methods to aid in reversing soil compaction. In order to help reduce the effects of soil compaction during construction, at a minimum the site should be deep-tilled and then chisel-plowed prior to establishing vegetation. As was shown in this study, runoff volume can be reduced substantially by carrying out these practices. If an increased level of runoff reduction is desired, compost may be amended to the soil as well. In addition to reducing the runoff volume even further, compost has many other advantages.

Amending the soil with compost appears to have many benefits and using compost offers great potential for reducing the amount of runoff from developed land and restoring ecological processes to degraded soils, while diverting a valuable natural resource away from landfills. In addition to helping reduce the effects of soil compaction, compost

provides nutrients, holds onto water longer, prevents soil disease, and grows vegetation faster than other conventional turf growing methods.

In addition to the environmental benefits of amending soil with compost, it pays for itself. When compost is tilled into the native soil during turf establishment using seed, the payback period for the extra upfront cost occurs between year 5 and 6 due to lessened fertilizer, pesticide, and irrigation costs. If sod is to be used instead of seeding, the payback period is even shorter, occurring during the first year (Chollak and Rosenfeld, 1998). Since compost can be obtained for little or no cost there is no reason that this practice should not be implemented more frequently.

Future Work

Additional studies on the benefits of deep tilling, chisel plowing, and compost-amendment need to be completed. This study utilized only one summer, one soil type, and one plot slope. Effects of the treatments may change significantly under different conditions. Additional research to study the individual effects of each treatment would be valuable, although chisel plowing must be completed in order to amend the soil with compost. It would also be beneficial to conduct tests for bulk density before and after the treatments are applied to get a direct measurement of how much compaction has been reversed. Care should be taken when testing for bulk density on the deep-tilled plots as the bulk density most likely varies with distance from where a ripper traveled.

Future studies could also improve upon the plot setup. Although the plot setup performed well, a reduced bucket size in the gauges may have provided more resolution in runoff and possibly would have recorded runoff from smaller storm events. It is unclear if this would in fact increase the resolution as one tip of the dumping bucket gauge accounts for only approximately 0.01 centimeters of runoff from the test plot area. Larger plots would also have been a benefit by reducing the possibility of edge effects between treatments and reducing the variability of runoff rates by having a larger area. If larger areas are used, consideration must be made to avoid a significant amount of detention when collecting runoff from the plot.

This study only measured runoff rates during the late spring through early fall and not through the non-growing season. It would be valuable to monitor test plots over the winter months, especially for runoff events on frozen ground. Many believe that a significant portion of the year's runoff may be during this time period. This may also be the time of year that the treatments tested in this study do not provide much benefit.

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