ABSTRACT

HAYNES, MATTHEW. Comparison of Methods to Remediate Compacted Soils for Vegetative Establishment. (Under the direction of Richard Mclaughlin).

Vegetation establishment on compacted construction sites is imperative to controlling erosion and sedimentation. Removal of topsoil and compaction of the subsoil presents multiple challenges in attempts to establish vegetation: low nutrient soils with little organic matter, high bulk densities, and low infiltration rates. The goals of this project are to quantify the impacts of soil compaction remediation methods on infiltration rate, stormwater runoff volume, and vegetation. Objectives are to measure: (1) maximum steady state infiltration rate (IR) over time; (2) quantity and quality of storm water runoff; and (3) percent ground cover, biomass production, and rooting depth of vegetation during early establishment. We evaluated four treatments on 3 sites: a compacted soil (C), a compacted soil with core aeration (A), a compacted soil with deep (20-30 cm) tillage (DT), and a compacted soil with deep tillage and compost (CT), which was implemented using a rear tine rototiller. Sites 1 and 2 received C, A and DT treatments and Site 3 received only DT and CT treatments. Plots were 2x1 meter for Site 1 and 0.6x1.2 meter for Site 2 with five replications of each treatment. Site 3 was also 0.6x1.2 meter but only had 3 replications of each treatment. At Site 1, runoff was collected in plastic tubs at the bottom of each plot, and samples were measured for volume and sediment. Infiltration rates were determined using a Cornell Sprinkle Infiltrometer. At Site 1, the A treatment had a higher erosion rate during two of four rain events and higher runoff volume during three of four rain events, when compared to the control and tilled treatments. Average event runoff ranged from 0 to 22%

(0-9.3mm), 10 to 60% (1.9-26.2mm), and 0 to 3.5% (0-1.1 mm) of the total rainfall for C, A, and DT, respectively. There was no difference between C and A plots for vegetative biomass and infiltration rate, but these were both greater in the DT plots. Tilled plots had an average IR of 15 cm hr^{-1}, compared to 0.16 and 0.21 cm hr^{-1} for C and A, respectively. At Site 2, IR and percent cover were the only 2 parameters measured. There were no significant differences in IR, due to an abundance of values too low to be read accurately by the infiltrometer, or percent cover between the three treatments due to poor vegetative establishment, which was 22, 16, and 23% for the C, A, and DT, respectively. Infiltration rates at Site 3 were 10X those at Site 2, but there no significant difference in average IR between CT and DT, which was the only measurement taken between the two treatments. Adding compost with deep tillage increased IR rates to 1.5X (10.1 cm hr^{-1}) that of deep tillage alone (6.4 cm hr^{-1}), but with high variation (CV=71%). The results suggest that deep tillage prior to seeding could minimize runoff, erosion, and surface-water sedimentation and maximize long-term vegetation growth.

Comparison of Methods to Remediate Compacted Soils for Vegetative Establishment

by
Matthew A. Haynes

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APPROVED BY:

Josh Heitman	William Hunt

Richard McLaughlin
Chair of Advisory Committee

BIOGRAPHY

Matthew A. Haynes was born and raised in Boiling Springs, North Carolina. He graduated from Crest High School in 2004 and went on to attend college at NC State. Matt developed a love for agriculture and the outdoors at a very young age and decided to pursue a degree in Agronomy at NC State. He graduated with a Bachelor's Degree in 2008 and then went on to pursue a Master's Degree in Soil Science under the direction of Dr. Rich Mclaughlin.

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CHAPTER 1: LITERATURE REVIEW

Soil compaction increases storm water runoff, which carries sediment and other harmful pollutants into water bodies. Urban areas may be compacted for structural strength or inadvertently compacted by heavy machinery during the construction phase (Gregory et al., 2006). Soil disturbance caused by heavy traffic can affect physical properties resulting in compaction and increased bulk density (Gregory et al. 2006), causing a decrease in vegetative stand (Balbuena et al. 2002).

Compaction and bulk density

Wang et al. (2008) showed that runoff increased 72% by wheel compaction on non-vegetated sites when compared to no-till crop production areas. This compaction can be very substantial due to the extreme weights of the machinery used during the construction phase. Botta et al. (2008) showed that as axel load increased, soil compaction increased when using standard radial tires and cross ply tires on a farm tractor. The two sites were a soil in direct sewing condition, which consisted of 9 years of direct drilling of winter wheat followed by soybeans, and a soil in conventional tillage. In treatments with axel weights greater than 40 kN, bulk density values were significantly higher for both soil conditions than in the control, which received no traffic, down to a depth of 300 mm. Heavy axel loads are also found on construction equipment, such as backhoes, dump trucks, and pickup trucks. Gregory et al. (2006) did a study using this equipment and reported weights of 6.3 Mg (7 t) for a backhoe and axle weights of 24.5 Mg (27 t), and 1.9 Mg (2 t) for a dumptruck and pickup truck, respectively. They showed that the heavier equipment, such as the dumptruck, increased mean bulk densities from 1.49 g cm^{-3} to 1.68 g cm^{-3}, when compared to the lighter pickup truck and backhoe, which had mean bulk densities of 1.61 g cm^{-3}. Although the differences between the heavier and lighter equipment were not statistical, they were numerically different. They reported that this could be due to sampling in the upper 10 cm of the soil rather than below 10 cm, which is where compaction tends to occur.

Randrup et al. (1997) showed that bulk density was consistently higher inside Danish construction areas than outside which led to root limiting densities as high as 1.9 Mg/m^3, with the controls averaging 1.74 Mg/m^3. The controls were found outside the construction areas in adjacent farmland and were unaffected by the construction traffic. The average densities of the soils used in Randrup et al.'s (1997) study ranged from 1.55 Mg m^{-3} to 1.65 Mg/m^3. An overestimation of 0.10-0.15 Mg m^{-3} was believed to be caused by the measurement technique, which was using a gamma ray density probe. The compaction can be variable depending on the moisture content at the time of impact. Vorhees et. al (1985) showed that bulk density varied on three different sites which consisted of a dry Nicollet soil, a wet Nicollet soil, and a Webster soil. All soil types were loaded by 9 and 18 Mg axel loads. Water contents were not significantly different in the upper 10 cm but below 30 cm the dry Nicollet had a water potential of about -1.5 MPa while the wet Nicollet had a potential of about -0.5 MPa. The Webster soil showed potentials from 0.3–0.5 MPa. The wet Nicollet and Webster soils showed significant increases in bulk density with the 18 Mg axel weights to depths of 50-60 cm, while dry Nicollet soil only showed differences up to 30 cm. The dry Nicollet soil showed little difference between the two axel loads but did show significant bulk density increase up to 15 cm with the 9 Mg axel and up to 30 cm with the 18 Mg axel. When the subsoil was wet, the bulk density was increased in the soil from the 30-

50 cm depth by about 0.8 Mg/m^3 when compacted using 9 and 18 Mg axle loads. When the same loads were applied to the soil on the dry Nicollet, no significant changes were seen in bulk density deeper than about 30 cm.

Infiltration and Surface Runoff

Infiltration rates are significantly reduced by compaction due to the destruction of soil structure, which increases surface runoff. The previously cited study by Gregory et al. (2006) showed that infiltration rates were decreased 70-99% under even the lowest of different compaction treatments. Infiltration rates were 861 mm hr^{-1} in the undisturbed state but decreased to 175 mm hr^{-1} post development as a result of vehicular compaction, an 80% reduction. At another location of the same lot, infiltration rates were decreased from 590 mm hr^{-1} to 8 mm hr^{-1}, a 99% reduction. Pitt et al. (1999) also performed a study on 10 different sites using a series of 153 double ring infiltrometer tests, which showed that mean infiltration rates decreased in sandy soils from 414.02 mm hr^{-1} to 63.5 mm hr^{-1} and in clayey soils from 223.5 to 17.8 mm hr^{-1} when sites were compacted, which was caused by construction activity, throughout Alabama. Kays et al. (1979) performed a study using double ring infiltrometers throughout the piedmont of North Carolina and found that infiltration rates in the Sudbury Suburban Watershed on excessively disturbed soils were 1 to 5% of neighboring forested areas and 3 to 15% of low disturbance areas. In the same watershed, studies also showed that areas that were previously forested had infiltration rates of 35.5% and areas that were previously cultivated had rates of 15.1% of the undisturbed forested areas. Generally, the only sites that contained infiltration rates of less than 1 cm/hr were the disturbed sites, while most undisturbed sites were substantially greater than 1cm/hr. Hamilton et al. (1999) showed that the youngest lawns evaluated had the lowest infiltration rates during a study on 15 residential lawns in central Pennsylvania. These two lawns, which were excavated during the construction phase, had average infiltration rates of 0.4 and 1.2 cm hr^{-1}. They found that 10 of the 15 lawns had average infiltration rates below 3 cm hr^{-1}. The remaining 5 lawns had certain properties that could have explained their higher rates, which were measured as high as 10 cm hr^{-1}. Practices such as minimal excavation during construction, years of core cultivation, and older lawns generally had the highest infiltration rates.

Runoff volume is affected by infiltration rate. Lower infiltration rates increase the chance that a site will increase runoff rate and volume. When rainfall events occur, the water has only 3 fates. It can infiltrate, evapotranspire, or runoff. Fullen (1985) showed that as infiltration rates decreased, ponding and runoff increased in the ruts caused by tractor tires. Samples were collected from the pools formed over the crusted ruts and were found to have sediment concentrations of 4000-6000 mg/L. Once the soil dried out and the sediment settled, it further impeded infiltration rates. Surface seals can be formed from this process. Rain drop impact causes the detachment of soil particles and smaller silt size particles can fill macropores and inhibit infiltration. Once these seals form, the hydraulic conductivity of the area decreases and surface runoff intensifies (Zhang et al., 1998). Their study showed that tilled treatments under higher rainfall amounts and intensities tended to form seals and produce runoff; whereas, under lower precipitation amounts and intensities the runoff remained low due to less seal formation.

Vegetation establishment on Compacted Soils

Vegetation establishment can also be affected on soils where the structure is destroyed via compaction. As mentioned previously, heavy machinery may cause impermeable layers to form in the soil which decreases infiltration and percolation, inhibiting root growth due to the anaerobic condition in the soil which this may create (Kozlowski, 1999). Not only does compaction inhibit root growth due to lack of water and oxygen, it also physically inhibits growth by destroying ground vegetation and causing dense layers that roots cannot penetrate or regenerate in (Balbuena et al. 2002). Chen et al. (2005) showed that no-tillage and conventional tillage treatments caused canola roots to concentrate above the compacted pan layer in their soils, which was found to be around 175 mm deep. Tillage to a depth of 257 mm allowed roots to penetrate much deeper in the profile due to loosened soil aggregates. The deep tillage treatment allowed roots to penetrate approximately 7% deeper than the no-till and conventional tillage treatments.

Plant height and yield are also affected by compaction. Abu-Hamdeh (2003) showed that as compaction increased corn height and yield decreased. Their plots were compacted using 8- and 19-Mg axel loads and compared to a control, which received no treatment. The final plant heights of the two compaction treatments were 6% and 10% lower for the 8- and 19-Mg treatments, respectively, when compared to the control. Over a 2-year period, the 8-Mg treatment reduced average corn yield by 13% and the 19-Mg treatment reduced yields by 20%. They also found a higher concentration of roots around the base of the plants for both compaction treatments; whereas, for the control they were found in both shallow and deeper portions of the profile. The previously cited study by Hamilton et al. (1999) showed no correlation between thatch density and infiltration rates on residential lawns but that proper inputs to minimize compaction during the construction phase may result in better plant growth, which could also help maintain infiltration rates.

Deep Tillage

Deep tillage, or subsoiling, is an accepted and effective method used to alleviate soil compaction in agricultural settings. Traffic pans, which are extremely dense layers, form in the subsoil and by breaking up these hardpans, deep tillage allows roots to penetrate deeper for water and nutrients (Varsa et al. 1997). Busscher et al. (2000) showed that soybean yield increased significantly under deep tilled treatments when compared to non deep tilled treatments on a Goldsboro loamy sand with a plow layer. Compaction was measured with a cone penetrometer. The readings were the lowest for the soils that were deep tilled that season when compared to those that were not deep tilled and those that were deep tilled in the previous season. Wheat and soybean yields were both reduced substantially for every megapascal increase in cone index by up to 1.75 Mg ha^{-1} and 1.81 Mg ha^{-1}, respectively. Deep tillage can positively influence high root densities around the base of the plant by loosening the soil media so that the roots are able to penetrate deeper in to the soil. Varsa et al. (1997) showed that corn root density as well as depth was greater in deep tilled treatments than in reduced and no-till treatments and corn grain yield was also greatest in the deep tilled treatment. They found that 35% of the roots were below 60 cm in the deep tilled plots when compared to the control where only 5% was found below 60 cm. The increase in rooting depth of the deep tilled plots was due to a decrease in bulk density caused by the tillage. Abu-Hamdeh et al. (2003) showed that subsoiling significantly decreased density by 2.3 and

2.6% for 8- and19-Mg compaction loads, respectively. They also found that subsoiling, reduced densities to close to what they were in their original conditions. Deep tillage also has a large impact on infiltration rates. Jones et al. (1994) compared the infiltration rates for a no-till system and stubble mulch tillage system. The treatments had similar infiltration rates in the beginning but the infiltration rates declined much more rapidly in no till. Over a 2-hour period the infiltration rate of the tilled treatment was 90% greater than the no-till system during fallow after sorghum. It was measured again during fallow after wheat and the tilled treatment had a 26% greater infiltration rate. Surface runoff was also highest in the no-till treatment with values exceeding the tilled treatment by as much as 81%.

Core Aeration

Aeration is also a common tool used to help establish vegetation on bare sites by homeowners as well as the commercial industry. Hollow tine and solid tine aeration are common practices found on golf courses and home lawns (Baldwin et al., 2006). Hollow tine aeration involves pulling a core out of the soil to make soil conditions more conducive for increased infiltration. Solid tine corers do not remove soil but produce a void. Tine size also plays an important role on the effectiveness of compaction relief. Baldwin et al. (2006) showed that the smaller diameter (1/4 inch) hollow tine produced a 34% higher infiltration rate than the larger (1/2 inch) diameter tine due to a decrease in pan formation when using the smaller diameter. Penetrometer studies by Shah et al. (2004) showed that aeration likely reduced impedence in their soil by alleviating some of the compaction. By decreasing impedence you allow roots easier access to water and nutrients. Murphy et al. (1993) found that core cultivation in compacted soils increased total porosity when using hollow and solid tine aeration, when compared to compacted controls. When using hollow tine aeration, the values for porosity were 19% and 21% higher than when compared to solid tine aeration.

In contrast, many studies show adverse effects of aerification. Brauen et al. (1998) showed that initially bulk density was not affected using aeration but as the number of annual aerifications increased, bulk density increased in both hollow and solid tine aerification. There was no difference in runoff from the aerated vs. non-aerated sites but TSS concentrations were up to 30% higher on the aerated sites due to surface disturbance. This causes more nutrients, such as P to runoff with the sediment. On construction sites it is likely that aerification is only done once but subsequent applications by homeowners could cause a decrease in vegetative stands. Franklin et al. (2007) also showed that in one of the fields where aeration was applied, total P concentration was higher in the runoff. This was due to rainfall impact after aeration that caused more soil particles carrying P to leave the site. Nitrogen uptake can also be influenced by aeration, as shown in a study by Shah et al. (2004). Though unexpected, they measured higher N uptake in a control site when compared to aerated and aerated with liquid dairy manure. There was no significant difference in the control vs. manure with no aeration which suggests that the aeration decreased N uptake, which could adversely affect crop growth.

The effects of aeration and deep tillage on grass establishment and surface runoff have clearly not been well established. Vegetation establishment on compacted construction sites can be very difficult due to excessive bulk densities as well as decreased porosity and infiltration rates. Once soils become compacted, the bulk density increases resulting in substantial increases in storm water runoff that is available to leave the site. Best management practices should be developed in order to counterbalance this phenomenon.

The purpose of this study was to determine best management practices for post construction urban areas. Objectives were to determine if hollow tine aeration and deep tillage were methods that could be used to (1) alleviate soil compaction, (2) improve and maintain infiltration rates, (3) improve grass establishment, and (4) decrease stormwater runoff and erosion.

CHAPTER 2: LAKE WHEELER EXPERIMENTS

Materials and Methods

Site Description

The study was located at the North Carolina State University Lake Wheeler Field Laboratory in Raleigh, N.C. Site 1 is located at the top of a fill slope made up of subsoil materials from an unknown site in Wake County. Approximately 18 m uphill is a native wooded area which was used to represent pristine site conditions for soil physical properties. The site was selected because it was an area with regular vehicular traffic which was expected to have some level of compaction. The area has a relatively uniform 3% slope.

Site 2 was approximately 6 m from an excavation just approximately 100 m uphill from Site 1 and consisted of fill material from the excavation.

Site 3 was located directly adjacent to Site 2 and exhibited similar characteristics. All three areas were chosen due to the presence of subsoil material at the surface similar to construction sites. There was vegetation present at each of the three sites before the study was conducted, consisting of a mixture of Bermuda grass (*Cynodon dactylon*), Large Crabgrass (*Digitaria sanguinalis*), and other weeds.

Plot Setup (All Sites)

Preliminary bulk density samples described below were taken over each site area in order to determine the most uniform and compacted areas for plot location. Once the area was chosen, the plots were further compacted using a pickup truck with a gross weight of 3084 kg (6800 lbs) (www.motortrend.com) and a gross pressure of approximately 1689 kPa (245 psi). Flags were placed eight inches apart, which was approximately the tire width of the pickup, and the truck was driven back and forth, repeatedly, until the entire area of each plot had at least 10 passes. Remaining vegetation that was not killed during the compaction treatment was killed using a glyphosate herbicide application in order to have a bare soil surface similar to a construction site. Just prior to plot installation, the dead vegetation was removed by running a string trimmer back and forth across the area.

Site 1

Once the area was selected based on the bulk density sampling, individual plots were flagged 2 m in length up and down the slope and 1 m wide. Fifteen plots were installed adjacent to each other with 0.15 m between them to allow for access without impacting the plots (Figure 1). To isolate each plot from outside runoff, plastic garden edging (10 cm high) was installed on all sides by driving the siding 3-5 cm into the soil. At the lower border, a gap was left into which a 10 cm pipe was installed. Gaps between the pipe and the edging, as well as between edging pieces, were filled using expandable foam (Great Stuff, DOW Chemical Company, Wilmington, IL). Runoff produced by rain events exited the plot through the pipe and into a 68 L plastic tub in an excavated ditch downhill of the plots (Figure 2). Assuming 100% runoff, the tub size allowed us to capture all runoff from a 0.5-year 24-hour storm in Raleigh N.C., which is 36.6 mm (NOAA Atlas 14).

A piece of plastic was draped over the pipe and the tub to insure that only runoff from each plot was entering the tubs and not precipitation (Figure 3). Water which accumulated in the ditch from adjacent areas was removed using a sump pump with a float switch.

Precipitation data was collected at the NC Climate Office rain gauge located off Lake Wheeler Rd (Figure 4). We obtained rainfall amount and intensity from the Climate Office database. The 15 plots were divided into 5 blocks of 3 plots and the treatments were assigned randomly within each block.

Sites 2 and 3

Plots were constructed to be 0.6 x 1.2 m, with colored flagging along the borders of each with each flag depicting a different treatment. Plastic borders were not used on these sites because only infiltration rate and vegetative measurements were taken.

Treatments (Sites 1 and 2)

Three treatments were used: deep tillage (DT), core aeration (A), and a control (C), which received no treatment. There were 5 replications for each of the three treatments. Each plot was also wetted with a hose for 1 min and allowed to dry 1 minute prior to DT or A. This procedure was repeated twice in order to moisten the surface soil, which was very dry and difficult for the tiller and aerator to penetrate.

The DT plots were implemented using a rear tine tiller (Troy-Bilt, Cleveland, OH) and plots were tilled to depths ranging from 25-30 cm (10-12 in; Figure 5). Due to the hardness of the surface crust a backhoe was used to loosen the soil in order to allow the tiller to penetrate the soil at Site 1. Once the plots were tilled, the depths of the tilled zones were measured by inserting a piece of rebar until the untilled soil was reached.

The A plots were plugged using a hollow tine aerator (Ryan, Johnson Creek, WI). Each of the A plots received ten passes until the plots were thoroughly treated (Figure 6). The average depth of 5 plugs in each plot was measured and averaged to estimate penetration depth, which was approximately 1.5 – 2 cm. The C plots received no treatments after compaction, but were watered prior to installation to insure that all plots were installed under similar moisture conditions (Figure 7).

Site 3

Two treatments were used: deep tillage (DT) and deep tillage with a compost amendment (CT). There were 3 replications of each treatment randomly assigned to plots. Tillage was performed using the same equipment as the previous sites and again, a depth of approximately 25 cm (10 in) was reached. No backhoe was used to break up the soil on this site because the soil moisture condition allowed the surface to be broken up using the rototiller. The compost that was used was a mushroom blend (Old Castle Lawn & Garden Inc, Atlanta, GA), and it was applied at a recommended 0.02 m^3 $1000m^{-2}$ (2 yd^3 1000 ft^{-2}) (Carolina Lawns, 11; Figure 8). The compost was applied prior to tillage and tilled in to the full depth of 25 cm (Figure 9).

Vegetation (All Sites)

Each plot received recommended fertilizer, lime, and seed mixes (NCDOT). Fertilizer (10-20-20) was applied at a rate of 560 kg ha^{-1} (500 lbs ac^{1-}) and pulverized dolomitic limestone at a rate of 3364 kg ha^{-1} (3000 lbs ac^{1-}). Fertilizer and lime were both applied after the DT and A treatments. They were raked into the DT plots on Sites 1 and 2 but were surface applied to the C and A plots to avoid disturbance. The fertilizer and lime were tilled in Site 3. Grass seed mix included tall fescue, centipede, and Bermuda grass (hulled) and was applied at 56, 11, and 28 kg ha^{-1} (50, 10, and 25 lbs ac^{1-}), respectively for Site 1, which was planted on April 27, 2009. Sites 2 and 3 had the same grass seed mix with the only difference being Bermuda grass was added at 35 lbs ac^{1-} due to fall and winter planting. Site 2 was planted on October 22, 2009 and Site 3 on January 26, 2010. Tall fescue seed viability was checked prior to planting Site 2 (Tetrazolium Testing Handbook, 1970) because it was purchased prior to planting Site 1 and all other seed was purchased new. All seed was applied directly after fertilizer and lime application. Once seeded, straw was applied at 3705 kg ha^{-1} (1.5 tons ac^{-1}) and fastened down using netting to avoid seed loss due to raindrop impact as well as to keep the straw in place. After all inputs were added each plot was wetted for 45 seconds using a hose to insure that each treatment had similar moisture conditions at the beginning of the experiment.

Bulk Density Measurements (All Sites)

Bulk density was measured using an AMS 6.4 cm (2 ½ in) diameter soil core sampler (AMS, American Falls, ID). Samples were taken from the top 2.5-12.5 cm of the profile with the top 2.5 cm being discarded. As mentioned above, initial samples were taken in order to isolate an area for both sites. Measurements were then taken directly before each treatment application. For Site 1, bulk density measurements were taken again at 7 weeks, Site 2 densities were taken at 11 weeks, and Site 3 were taken at 3 weeks after treatment application. This was done in order to see the treatment effects on the pretreatment bulk densities. A single core was taken from each plot and brought back to the lab and dried at 103-105°C and analyzed for bulk density. Particle size analysis was also done on each of bulk density samples using the hydrometer method (Gee and Bauder, 1986).

Stormwater Runoff Measurements (Site 1 Only)

After each rain event, polyacrylamide (PAM) was added to the samples in order to settle the suspended sediment. The PAM was applied as a concentrated solution of 1 g/liter to bring the concentration in the runoff to 2-3 mg L^{-1}. Depending on the size of the sample, this was done either in the lab or in the field. The supernatant was decanted from the container and the volume was measured. The sediment remaining was oven dried at 103-105°C for 24 hours and weighed. Some samples did not fully settle after flocculation, and these were subsampled and analyzed for Total Suspended Solids (TSS) by filtration (Clesceri et al., 1998). The TSS values were converted to sediment loss and added to the amount of sediment settled using PAM to find the total sediment loss from each plot.

Total stormwater runoff was determined by collecting and measuring all runoff in the tubs after each storm event. Rainfall values were obtained from the NC Climate Office for the Lake Wheeler Road Field Laboratory weather station (http://www.nc-climate.ncsu.edu/cronos/search.php), located approximately 1.6 km from the plots.

Maximum Steady State Infiltration Measurements (All Sites)

Infiltration rates (IR) were determined using both simulated rainfall and the Cornell Sprinkler Infiltrometer (Cornell University, Ithaca, NY) at Site 1. The Cornell method was the only one used on Sites 2 and 3. The simulated rainfall method was performed by suspending a single Fulljet 1/2HH-SS50WSQ nozzle 3 meters above 2 adjacent plots simultaneously, and spraying at a pressure of 42 kPa to provide approximately 100 mm h^{-1} rainfall as shown by Volf et al. (2007). We were able to measure two plots at a time due to the circumference of the spray pattern (Figure 10). Before simulated rainfall began on each plot, the nozzle was calibrated by placing 5 tin cups, which were approximately 300 cm^3, in each plot and raining on each of them for 5 minutes. The water in each tin was then measured and averaged to get the rainfall rate. Once calibration was complete, the simulator was run for at least 45 minutes until steady state runoff was achieved. Runoff was collected every 3 min for 20 sec intervals, which was based on the amount of runoff generated, using a graduated cylinder at the point of discharge from the PVC pipes.

The Cornell Sprinkler Infiltrometer (CSI) was also used as an alternative method to measure IR's on Site 1 and was the only method used on Sites 2 and 3 (Figures 11-12). The device was calibrated to provide a 250 – 300 mm hr^{-1} rainfall (van Es et al. 2003). This device is similar to the one shown by Ogden et al. (1997). The infiltrometer was filled with water and allowed to run at a constant rainfall rate until the runoff rate attained steady state. The infiltration rate was calculated from the difference between the water volume used during the test and the amount of runoff, using the equation below:

$$\mathbf{i_t = r - ro_t}$$

- I_t = Infiltration rate (cm min^{-1})
- r = rainfall rate = [H1-H2] / T_f (cm min^{-1}) where H1 is the height of water in the infiltrometer at t=0, H2 is the height of water at the end of the measurement period, and T_f is the time at which the water level at H2 is read.
- ro_t = runoff rate = V_t / (457.30*t) where 457.30 is the area of the ring (cm min^{-1}), V_t is the runoff volume measured in the cylinder, and t is the time interval for which water was collected.

Above Ground Biomass Determination (Sites 1 and 2)

Above ground biomass was measured by randomly selecting three 20 x 20 cm squares in each plot and removing all vegetation in each of the squares using scissors. The squares were found in a grid that was placed over each plot (Figure 13). The vegetation from each square was combined, oven dried at 103-105°C for 24 hrs, and weighed.

Vegetative Coverage – All Sites

Visual estimations of percent coverage were made independently by four people to determine the vegetative coverage of each plot. The estimates from each person were averaged for each plot.

Root Density and Depth (Site 1 Only)

For measuring root density and depth, a modified profile wall method (Bohm, pg. 48) was used. Pits were dug in each plot down to a depth of approximately 1 m using a backhoe (Figure 14). A pressure washer was used to wash the face of the pit to remove loose soil and expose the roots. A 50x50 cm grid, which consisted of 100 5x5 cm squares, was placed level with the soil surface and fastened to the profile wall using ground staples and the top of the grid (Figure 15). The number of roots in each of the 50 squares was counted and averaged at each 5 cm depth increment (Appendix 1-a). The results were then placed into one of three categories using a rating system (Table 1). The rating system was chosen due to the fibrous rooting system of the vegetation planted and this method allowed us to be more consistent in counting the roots. Once the average rooting density for each replication was calculated, they were combined for the rooting density at each depth for the three treatments.

Data Analysis

SAS Software was used to perform all statistical analyses (SAS version 9.1, SAS Institute, Cary, NC). Analysis of Variance (ANOVA) was performed on all infiltration and vegetation data to analyze main effects and Tukey's Least Significant Difference (LSD) was used to separate treatments. For stormwater runoff/sediment data, a linear mixed model was fitted for each response, with storm, treatment and their interaction considered as fixed effects, and rep, rep*treatment considered as random effects. The Kenward-Roger approximation was used in the calculation of denominator degrees of freedom for the fixed effects and estimation of the standard error of the least squares means. Tukey's Least Significant Difference (LSD) was used for means separation. Error rates were controlled at α=0.05.

Results and Discussion

Bulk Density

Site 1

Prior to treatments, the average bulk density in the compacted area was 1.6 g cm^{-3} and there were no significant differences in bulk density along the entire designated area (p=0.48). This was ideal and insured that the area started out with consistent densities. The bulk density taken at 7 weeks after treatment was unchanged in the C and A plots but significantly reduced in the DT treatment (Table 2).

Site 2

There were no differences in bulk densities in the C and DT plots prior to treatment, but the A plots started out with an average bulk density of 1.7 g cm^{-3}, which was significantly higher than the other two treatments (Table 3). After 11 weeks, the DT plots had a significantly lower average bulk density than it did pre-treatment, with the averages decreasing from 1.6 to 1.4 g cm^{-3} (p=0.001). The C and A treatments showed no differences in bulk density from their pre-treatment values.

Site 3

The average pre-treatment bulk densities of Site 3 were similar for the composted+tilled (CT) plots and the tilled only (DT) plots (Table 4). Five weeks after treatment installation, the bulk densities of both treatments were lower than their pretreatment values and were measured at 1.3 g cm^{-3}. However these differences were not statistical due to variability. The CT plots were also not significantly different from the DT plots after 5 weeks. The decreased bulk densities of the DT plots in all three sites is consistent with a study by Materechera (2009). He showed that a vegetable field which received deep tillage twice a year had significantly lower densities than neighboring sites that received either no tillage or tillage followed by a disc harrow at the soil surface. These measurements were taken approximately 11 years after field establishment. He stated that these results could have been from the loosening of soil particles through tillage, which is similar to the three sites of this study. Taser et al. (2004) also showed that bulk densities were lower on a clayey soil in three conventional tillage systems when compared to no-till and reduced till systems in the 0-15 cm layer. At a depth of 15-30 cm, no-till and reduced tillage systems had similar bulk densities but they remained higher than the conventional tillage treatments.

Maximum Steady State Infiltration

Site 1

Under simulated rainfall (SR), the average infiltration rates (IR) for the C, A, and DT treatments were 2.70, 2.22, and 5.67 cm hr^{-1}, respectively (Table 5). There were no differences in average IR between the C and A treatments but the DT treatment was significantly higher ($p=0.02$). The rainfall simulator produced similar amounts of precipitation in each treatment and differences were not significant ($p=0.69$).

The Cornell Sprinkler Infiltrometer (CSI) produced simulated rainfall rates more than 2X the SR (Table 6), which will be discussed later in this section. Similar to the SR, there were no differences in IR between the C and A plots, averaging 0.16 and 0.21 cm hr^{-1}, respectively. Infiltration was two orders of magnitude higher in the DT plots (14.4 cm hr^{-1}; $p=0.002$). This is similar to the results of Freese et al. (1993) who found that the loosening effect of tillage in a non-trafficked area improved infiltration relative to a more compact no-till treatment immediately after tillage with a chisel plow. The tillage increased the IR by 0.5 cm hr^{-1}, improving it from 4.5 to 5 cm hr^{-1}. However, they found no differences in measurements in the non-trafficked area after 30 min so this suggested that surface sealing occurred in the tilled plots.

The average IR for the CSI was much lower for C and A treatments and higher for the DT treatment compared to the SR method. Raindrop impact is more intense under the SR method, where the precipitation is falling from 3 m, compared to the CSI method, with a 5 cm drop. The higher impact can dislodge soil particles and cause them to re-deposit to form surface crusts. These surface seals can substantially lower IR because of their low hydraulic conductivities (Zhang et al. 1998). Since the vegetation was not fully established during the SR testing, which was measured after 8 weeks, the surface seals could explain the lower IR in the DT plots. The CSI method was conducted 2 weeks later so vegetative cover may have slightly improved.

The C and A plots had lower IR by the CSI method compared to the SR method. This could be due to an uneven distribution of rainfall throughout the sampling period when using the SR method. As previously mentioned, the nozzle was calibrated prior to measurement but it was not measured throughout the time it took to reach steady state runoff. If the rainfall rate varied throughout the collection period this could have caused an underestimation of rainfall which would have led to lower infiltration rates. A decrease in rainfall rate could have been caused by wind or even varying pressure coming from the hose. The runoff samples were collected in 1 L graduated cylinders measuring the samples in 10 mL increments. For values that fell in between the 10 mL markings, the readings were estimated to the nearest 5 mL, which also introduces uncertainty into the measurement.

Another possibility for the lower IR for the C and A treatments could be that lateral movement of water increased the IR using the SR method. The CSI method includes a barrier buried 7.5 cm into the soil, restricting lateral movement. The SR method only restricts water flow down to approximately 2.5 cm, which is the depth of the plot edging. This creates a larger volume for soil water to percolate throughout the profile. The DT plots had lower IR by the SR method. Again, this could be attributed to the rainfall impact dislodging the freshly tilled soil particles and causing them to seal the soil surface.

The correlation between bulk density and IR using the SR method was significant (Figure 16). There was also a trend found using the CSI method even though IR in the control and aerated plots were extremely low (Figures 17-18). In general, IR decreased as BD increased. One reason for this is that soils with lower bulk densities have greater pore space, which permits rapid infiltration (Brady and Weil, pg. 112).

The DT treatment resulted in the lowest bulk densities and the highest IR's using both infiltration methods. The A treatment did not result in any measureable change in bulk density or IR relative to the control. For this particular site, soils with bulk densities above approximately 1.4 g cm^{-3} had greatly reduced IR.

There were no significant correlations between clay content and IR using either of the two methods (Appendices 1-b-1-c). Particle sizes varied substantially from the first to the last plot, ranging from clay loam to sandy loam, although no correlations could be made between any of the measured variables with sand or clay content.

Site 2

At Site 2, IR was measured only by CSI. There were no significant differences in IR for any of the treatments at Site 2 (p=0.56, Table 7). Infiltration was too low to be read by the infiltrometer on 10 of the 15 plots. Compared to Site 1, IR was lower for the C and A treatments and much lower (25X) for the DT treatment. The IR in the DT plots was more than 3X the C and A plots but the variability was too high to detect any significant differences (CV=257%).

The lower IR at Site 2 relative to Site 1 may have been the result of poor vegetative establishment and poor root growth, which might have allowed the soil to settle more than at Site 1. The sparse vegetation also left the soil more exposed than at Site 1, leaving it more susceptible to raindrop impact and surface crusting. Site 2 received precipitation 6 out of 10 days after treatment, with the largest being a 12.7 mm storm with a peak intensity of 5 mm hr^{-1}, on the 10^{th} day. These rain events could have moved seed around and caused impermeable surface layers that may have inhibited germination and root penetration. Site 2 IR measurements were taken 7 weeks (early December) after installation to allow the vegetation to become established, but unusually cold temperatures during the period prevented significant plant growth. During this period, there were a total of 23 storms with 210 mm of precipitation, and with the plots essentially bare considerable raindrop impact and crusting could have occurred.

The average clay content of all plots was 26% for Site 1 and 38% for Site 2, suggesting that if surface crusting occurred, the latter would have more fine clay particles to clog the soil pores and impede IR (Appendices 1-d, 1-e, and 1-f).

Particle sizes ranged from clay loam to clay across the plots at Site 2. As expected, there were no significant relationships between IR and either bulk density (Appendix 1-g) or clay content (Appendix 1-h) due to the majority of the plots having no measureable infiltration.

Site 3

At Site 3, IR was measured only by CSI. There were no significant differences in IR's for either of the two treatments for Site 3 (p=0.52, Table 8). Numerically, the composted + tilled (CT) treatment resulted in an IR 1.5X that of the DT treatment, but no differences were found due to high variation (CV=71%).

This numerical difference in IR could be attributed to higher surface roughness generated by the incorporation of compost, which delays runoff (Govers et al. 2000). Measurements were only taken directly after compost was applied so the long term effects are unknown for this study at this time. The rainfall rate on Site 3 was set to 2X the rate of Site 2 due to the longer time it was taking for runoff to occur, yet IR's were substantially higher on Site 3. The main difference between the two sites was that IR's were taken directly after treatment application on Site 3 to prevent surface crusting caused by raindrop impact, while measurement on Site 2 were taken 7 weeks after treatment to allow vegetation establishment. IR was correlated with bulk density and clay content and there were trends present with both comparisons (Figures 19-20).

As bulk density decreased, IR rate increased under CT and DT treatments (Figure 19), which was similar to the relationship at Site 1. Bulk density seems to be the key characteristic at Sites 1 and 3 that controlled IR (Figure 21-22). Clay content also seemed to increase with IR for both treatments at Site 3 so this rules out the possibility of soil texture being the limiting factor for its lower IR, when compared to Site 1 (Figure 20). The clay texture was consistent throughout all 6 plots at this site (Appendix 1-i).

There were no differences in cumulative infiltration rates using the CSI method prior to runoff for any of the treatments at any Site (Tables 9 and 10). Numerically, the DT plots infiltrated approximately 3X that of the C and A treatments at Site 1 but the differences were not statistical. At Site 2, runoff began within the first minute on every treatment, which meant that the cumulative infiltration prior to runoff was much less than could be accurately measured using the infiltrometer. At Site 3, there were also no differences but both CT and DT treatments had high cumulative infiltration amounts, which were 6.6 and 4.7 cm, respectively (Table 10). This indicates that these treatments could infiltrate large amounts of water before runoff even though the steady state IR may be low at times.

Vegetative Establishment

Dry Weight and Percent Coverage – Site 1

The vegetative cover of the C, A, and DT treatments were 65, 62, and 85%, respectively (Figure 23). There were no significant differences (p=0.06) although DT was much higher numerically than the other treatments. A similar trend was found for biomass but the differences were significant (Figure 24; p=0.002).

These data suggest that tillage improves vegetative biomass and percent coverage. Chen et al. (2005) showed that subsoiling at 264 mm, which is the depth of tillage in this study, improved crop emergence and had a much higher plant population and crop yield when compared to a conventionally tilled (88 mm) and a no-tilled system. They also stated that this could be due to the subsoiled plots having a better ability to retain water in the dry periods and drain water under wet conditions.

There does seem to be some correlation between the two measurement techniques, as expected (Figure 25). The positive relationship between cover estimates and above ground biomass suggests that the ocular estimates closely followed the actual amount of vegetation present on the plots. Both cover estimates (data not shown) and above ground biomass were also correlated with bulk density (Figures 26 and 27). There was no correlation between cover estimates and clay content for this site (Appendix 1-j).

As bulk density increased, vegetative biomass had a decreasing trend using both ocular and above ground biomass measurement techniques. Similarly, Balbuena et al. (2002) found a 58% yield reduction of grassland production on high intensity trafficked soils, where 10 passes with a tractor increased bulk density by greater than 50% compared to a non-trafficked area. Compaction level was strongly related to traffic intensity in Balbuena et al.'s study.

The correlation between SR-IR and both vegetative cover and biomass was not particularly strong but it was significant, with a trend of both measurements increasing together (Figures 28-29). This relationship is also evident when using the CSI method (Figures 30,31, and 32) even though there were an abundance of zeros. These data suggest that IR and vegetative establishment are improved when you have higher porosity and lower bulk density, which are both achieved through deep tillage. Environmental conditions were better for grass establishment when we established Site 1 due to warm weather, which may have been at least partly responsible for maintaining the reduced BD and higher IR, caused by tillage, compared to Site 2. The higher IR on Site 1 for the DT treatment itself probably allowed for better moisture availability, aeration, and drainage, enhancing grass growth and establishment.

Site 2

Seed Viability

A TZ test was performed on the tall fescue because it was purchased at the time of planting for Site 1, whereas the bermuda and centipede grass were purchased prior to planting Site 2. It was found that 42 of 50 seeds (84%) were living at the time Site 2 was planted, which indicated good seed viability.

Vegetative cover was the only vegetative measurement taken on Site 2. There were no differences in cover estimates between the treatments but the mean values were much lower than at Site 1 (Figure 33). This could be due to a number of factors including cooler weather, soil texture, bulk density, IR, and surface crusting.

The correlation between vegetative cover and clay content were not evident for either site (Appendices 1-j-1-k). This indicates that texture was not the driving variable controlling vegetative growth. Also, neither BD nor IR were correlated with vegetative cover at Site 2 (Appendices 1-l-1-m).

These data have shown that particle size, bulk density, and IR's do not seem to be controlling vegetative establishment on Site 2. Surface crusting by rainfall impact could have played a key role during this study. The plots did receive rainfall 6 of 10 days after treatment application. As mentioned in the section above, straw was added to each of the plots but there was no vegetative cover at this time.

Rooting Density

Site 1Only

There were no differences in rooting density among the three treatments in the upper 15 cm of the soil profile (Table 11). The rooting systems of the C and A treatments were very dense and had numerous short roots; whereas, the DT treatments had longer roots that extended deeper through the profile. This could be due to the tillage loosening up the upper part of the soil matrix which made it easier for roots to extend throughout the profile. Below 15 cm the DT plots had higher average root densities than the C and A; the latter two which again showed no differences (Figure 34). These differences were down to a depth of 50 cm, with each 5 cm increment at $p<0.02$. These results are consistent with a study done by Erbach et al. (1992). They showed that different tillage tools, which consisted of chisel, moldboard, and paraplow systems, all reduced soil bulk density and penetration resistance to the depth of tillage when compared to a no-till system. Due to the high levels of compaction, we were only able to aerate to approximately a 1 inch depth, which could explain the poor results for root penetration in this study.

Sediment Loss

For Storm 1, sediment loss was 6.0, 35.2, and 8.5 kg ha^{-1} for the C, A, and DT treatments, respectively (Figure 41). The A treatment resulted in numerically higher amounts of sediment than the C and DT treatments, but these differences were no significant due to variation. This is consistent with the higher stormwater runoff on the A plots (Figure 34). There was a larger volume of water leaving the aerated plots carrying sediment. The C and DT treatments were not significantly different in sediment loss for the first event. While runoff volume was low for the DT treatment, the loosening of the soil surface apparently resulted in high sediment concentrations in the runoff. These results are consistent with Zhou et al. (2009) who showed that erosion and sediment yields could be reduced by 90% in no-till and strip till systems when compared to a chisel plow system.

For Storm 2, sediment loss was 14.0, 130.6, and 0 kg ha^{-1} for the C, A, and DT plots respectively (Figure 41). The A plots lost the highest amount of sediment of the three treatments ($p<0.0001$) but there were no differences in the C and DT plots due to high variability. The spike in sediment loss for the A treatment is due to the high peak intensity of storm 2. Numerically, there was higher sediment loss in the C plots than in the DT plots because the DT plots produced no runoff during this event.

Sediment loss was 8.7, 15.4, and 0.9 kg ha^{-1} for the C, A, and DT plots, respectively, for storm 3 (Figure 41). There were no differences between any of the treatments for this storm event, but A treatment sediment losses were much lower when compared to the first two events. For Storm 4, sediment loss was 15.2, 13.5, and 3.4 kg ha^{-1} for the C, A, and DT plots, respectively (Figure 41), and there were no significant differences between any of the treatments.

The higher sediment losses on the A treatments could be attributed to the surface disturbance caused by the aeration. The higher runoff amount suggests that the aerator disturbed the surface but also compacted it while pulling out small cores of soil. This combination resulted in more erosion and would actually worsen the surface condition compared to the compacted soil alone.

Conclusions

- Tillage significantly reduced bulk density on all sites.
- Aeration had no affect on bulk density on any site.
- Tillage increased IR on Site 1, using both measurement techniques (SR and CSI), but had no affect on Sites 2 and 3 when compared to the control, using only the CSI method. Average IR were approximately 50% higher at Site 3 for the CT, however, variation among plots resulted in no statistical differences.
- Infiltration rate decreased as bulk density increased at Sites 1 and 3. This relationship was not present at Site 2, but 10 of 15 plots had IR so low the infiltrometer could not measure it.
- Poor vegetative growth and surface sealing could have played a large role at Site 2, which would help explain the low IR.
- Aeration had no effect on IR on any site.
- Tillage significantly increased vegetative cover at Site 1 but not at Site 2. This measurement was not taken on Site 3.
- Above ground biomass was also significantly increased by tillage at Site 1, which is the only site this measurement was taken on.

- There were no differences in rooting density in the upper 15 cm of the soil profile between any treatments at Site 1, the only location where this was measured.
- Tillage significantly increased rooting density below 15 cm at Site 1.
- Shallow (2-3 cm) aeration did not improve rooting density at any depth.
- It could be that good vegetation establishment was responsible for the high IR at Site 1, which was increased by implementing tillage.
- There were no differences in vegetative measurements at Site 2 for any treatment.
- Aeration increased stormwater runoff during 2 of 4 storm events. Although there were no changes in bulk density, it is possible that aerating the plots caused further compaction which would help explain the higher runoff.
- Tillage had no affect on stormwater runoff during any storm event when compared to the control due to high variability. The DT treatment did produce numerically lower runoff for every storm event, ranging from 2-20% lower than the control, but the differences were not significant due to variability.
- Aeration increased sediment loss during 1 of 4 storm events, while tillage showed no differences in sediment loss for any event, when compared to the control.

Tillage decreases bulk density, which would be expected to improve water percolation, infiltration, and root/shoot growth. Bulk density was correlated with IR on Sites 1 and 3. As bulk density increased, IR decreased, indicating that it is an important factor that should be addressed when implementing stormwater control plans.

The plots with the highest vegetative cover, which were the DT plots, generally had the highest IR at Site 1. This was expected due to the fibrous rooting systems ability to maintain the loosening of the soil caused by tillage. The relationship between bulk density and vegetative cover at Site 1 suggests that quick vegetative establishment could also have been one of the main variables that controlled IR, along with the decreased bulk density from tillage operations. At Site 2, the infiltration rates and vegetation establishment were very low 7 weeks after plot establishment, even though bulk density was significantly decreased by tillage. A combination of poor germination and high rainfall after treatment may have resulted in surface sealing, which in turn greatly reduced IR. To avoid this, IR was measured directly after treatment installation at Site 3 and the rates were much higher than at Site 2 for both DT and CT treatments. However, there was a slight difference in average bulk density following tillage between the two sites, which could have also caused the higher IR on Site 3. The incorporation of compost did not improve IR at Site 3 and continued measurement of IR should be conducted to determine the long-term impact of compost on maintaining IR.

The differences in temperature, rainfall, and wind during the time of early germination between the three sites could explain some of the variation in grass growth and IR. Site 1 was planted under ideal weather conditions in the early summer, while Sites 2 and 3 were planted in the winter. This is likely a major factor in the development of a healthy stand of grass on Site 1 and a poor stand of grass on Sites 2 and 3.

Tillage showed no effect on stormwater runoff and sediment loss when compared to the control due to high variability, although it did provide better results than the aerated treatment. This is due to increased infiltration rates caused by tillage on Site 1, which allowed more water to enter the soil rather than runoff. The tillage treatment had the lowest runoff and sediment losses for all storm events, although differences were not statistical.

Aeration had no effect on bulk density, IR, and vegetative growth at Site 1, but it did have a negative effect on runoff and sediment loss. It is possible that the aerator caused compaction while removing relatively shallow cores, resulting in higher stormwater runoff and sediment loss when compared to the control. Since the bulk density was unchanged, the loose soil removed by the hollow tines was available when runoff occurred, leading to higher sediment concentrations in the runoff. Cores were only able to penetrate up to approximately 2 cm due to the dry conditions and high compaction levels. A moist soil surface is imperative when aerating compacted soils in order for the aerator tines to extend down to their achievable depths. On a construction site, much larger and heavier equipment would be used to aerate the soils which could increase the penetration depths of the aerator tines and potentially provide better results.

Soil compaction has shown negative impacts on stormwater runoff, infiltration, and vegetative establishment. Deep tillage is a practice that can be used in order to loosen the soil for quicker vegetation establishment in the summer months, which in turn, can help maintain higher IR. This is important from a management aspect because by increasing IR and grass coverage, more water is forced to enter the soil surface rather than flowing offsite or into other stormwater infrastructures. By decreasing the amount of water that flows through ditches and into sediment basins, it is possible that stormwater infrastructure sizes can be reduced which can help save labor costs. Also, by decreasing runoff, sediment loss is decreased and this allows for less maintenance on existing diversion ditches and sediment basins.

Tillage prior to extended periods of rainfall on construction sites may produce less satisfactory results due to the possibility of surface crusts forming and inhibiting IR, which increases runoff and erosion from construction sites. Future research should be conducted using tillage and aeration equipment comparable to that on a construction site in order to see how the size of the equipment used affects penetration depths, as well as all other parameters that were measured in this study. Time to runoff and cumulative infiltration are two other important aspects of this research that should be evaluated. If time to runoff and cumulative infiltration prior to runoff is high, then low steady state IR may not have such a negative impact on stormwater runoff.

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TABLES AND FIGURES

Table 1. Root Density rating system for modified profile wall method of analyzing roots.

Number of roots	Rating
0	0
1-10	1
11-30	2
31+	3

Table 2. Average pre-treatment and post-treatment bulk density measurements for Site 1.

Treatment	**Bulk Density**	
	Pre-treatment	**7 weeks**
	--------------------------g cm^{-3}	-------------------------
Control	1.6a	1.6a
Aerated	1.6a	1.6a
Tilled	1.6a	1.4b

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

Table 3. Average pre-treatment and post-treatment bulk density measurements for Site 2.

Treatment	**Bulk Density**	
	Pre-treatment	**11 weeks**
	---------------g cm^{-3}---------------	
Control (C)	1.6a	1.6a
Aerated (A)	1.7a	1.7a
Tilled (DT)	1.6a	1.4b

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

Table 4. Average pre-treatment and post-treatment bulk density measurements for Site 3.

Treatment	**Bulk Density**	
	Pre-treatment	**5 weeks**
	---------------**g cm^{-3}**---------------	
Composted+Tilled (CT)	1.5a	1.3a
Tilled (DT)	1.6a	1.3a

Means followed by the same letter within a row are not statistically different (p=0.16).

Table 5. Average IR's using the SR method for Site 1.

Treatment	Avg. rainfall rate	Avg. infiltration rate
	------------------------cm hr^{-1}---------------------------	
Control	9.75a	2.70b
Aerated	10.62a	2.22b
Tilled	10.57a	5.67c

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

Table 6. Average infiltration rates using the CSI method for Site 1.

Treatment	Avg. rainfall rate	Avg. infiltration rate
	----------------------------cm hr^{-1}-------------------------------	
Control	24.0a	0.16b
Aerated	23.0a	0.21b
Tilled	28.2a	14.8c

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

Table 7. The average IR's using the CSI method for Site 2.

Treatment	Avg. rainfall rate	Avg. infiltration
	--------------------------cm hr^{-1}	-------------------------
Control	28.26a	0.1a
Aerated	23.92a	0.18a
Tilled	21.86a	0.6a

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

Table 8. The average IR's using the CSI method at Site 3.

Treatment	Average rainfall rate	Average infiltration
	------------------------------cm hr^{-1}	--------------------------------
Compost + Tilled (CT)	58.5a	10.1a
Tilled (DT)	57.5a	6.4a

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

Table 9. Average cumulative infiltration prior to runoff at Sites 1 and 2.

Treatment	Avg. Cumulative Infiltration prior to runoff (cm)	
	Site 1	Site 2
Control (C)	0.16a	0a
Aerated (A)	0a	0a
Tilled (DT)	2.9a	0a

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

Table 10. Average cumulative infiltration prior to runoff at Site 3.

Treatment	Avg. Cumulative Infiltration prior to runoff (cm)
Compost + Tilled (CT)	6.6a
Tilled (DT)	4.7a

Table 11. Root density ratings for each treatment.

Depth (cm)	**Average Rating**			
	Control	Aerated	Tilled	P-value
5	3.0a	3.0a	2.8a	0.41
10	2.6a	2.8a	2.8a	0.75
15	2.1a	2.1a	2.6a	0.16
20	1.4a	1.3a	2.6b	0.0002
25	0.9a	0.7a	2.4b	<0.0001
30	0.4a	0.4a	1.7b	0.001
35	0.4a	0.4a	1.1b	0.008
40	0.2a	0.3a	0.7b	0.02
45	0.2a	0.3a	0.7b	0.02
50	0.2a	0.2a	0.6b	0.02

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

Table 12. Rainfall data for each of the four storm events. Antecedent Dry Period (ADP) is difference in days between the first rainfall event of a given storm and the last day of the previous rainfall event.

	Date	Rainfall Depth (mm)	Peak Intensity ($mm\ hr^{-1}$)	ADP (days)	Days after planting
Storm 1	5/4-5/6/09	19.6	3.6	7.83	7.83
Storm 2	5/17-5/18/09	43.7	29.0	1.29	20.4
Storm 3	5/28/09	11.7	11.2	7.29	31.9
Storm 4	6/4-6/5/09	13.5	6.9	6.88	38.8

Figure 1. Diagonal view of the plot layout at Site 1.

Figure 2. Tubs were placed in the ditch in order to receive stormwater runoff from the plots on Site 1.

Figure 3. Plastic was placed over each tub to insure that no direct precipitation entered and diluted the sample.

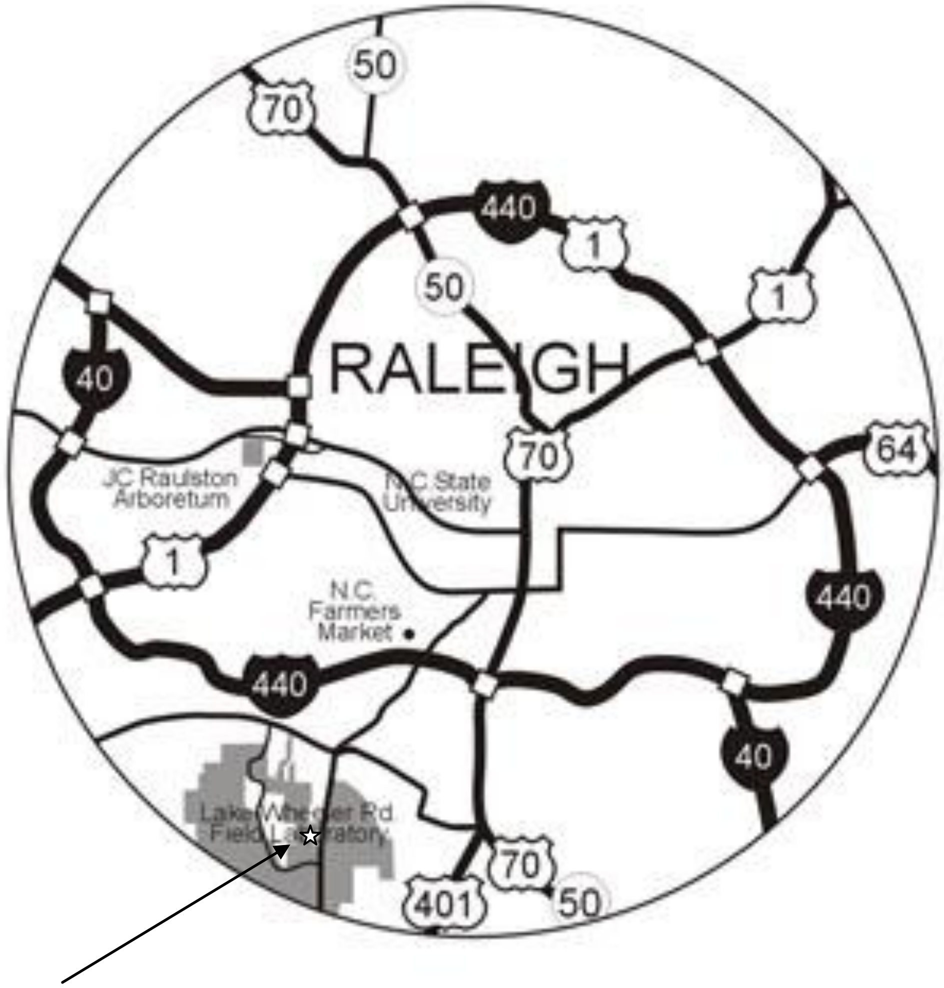


Figure 4. The rain gauge used was located off Lake Wheeler Rd. in Raleigh N.C.

Figure 5. Tillage was done using a rear tine tiller for all sites.

Figure 6. Plots were aerated with a hollow tine core aerator at Sites 1 and 2.

Figure 7.   A single replication of each treatment is shown immediately

f

Figure 8. Mushroom compost blend applied to Site 3 at 2 $yd^3\ ac^{-1}$.

Figure 9. Compost was tilled in to a depth of approximately 8 inches.

Figure 10. Infiltration using the Simulated Rainfall Method.

Figure 11. Cornell Sprinkler Infiltrometer.

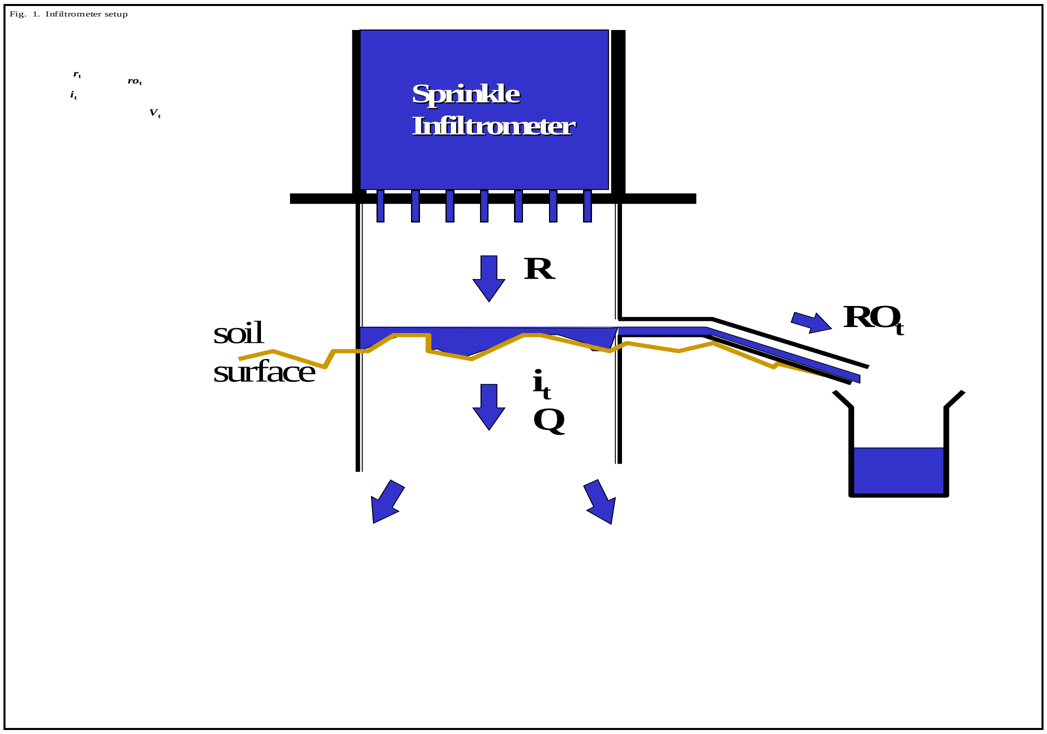


Figure 12. Schematic of Cornell Sprinkle Infiltrometer

Figure 13. Grid used for above ground biomass measurements. Each inner square was 20x20 cm and three were randomly chosen for harvest.

Figure 14. Pits were dug 3 ft deep in each plot for root analysis.

Figure 15. A 50x50 cm grid was fastened to the soil profile wall and roots were rated in each square.

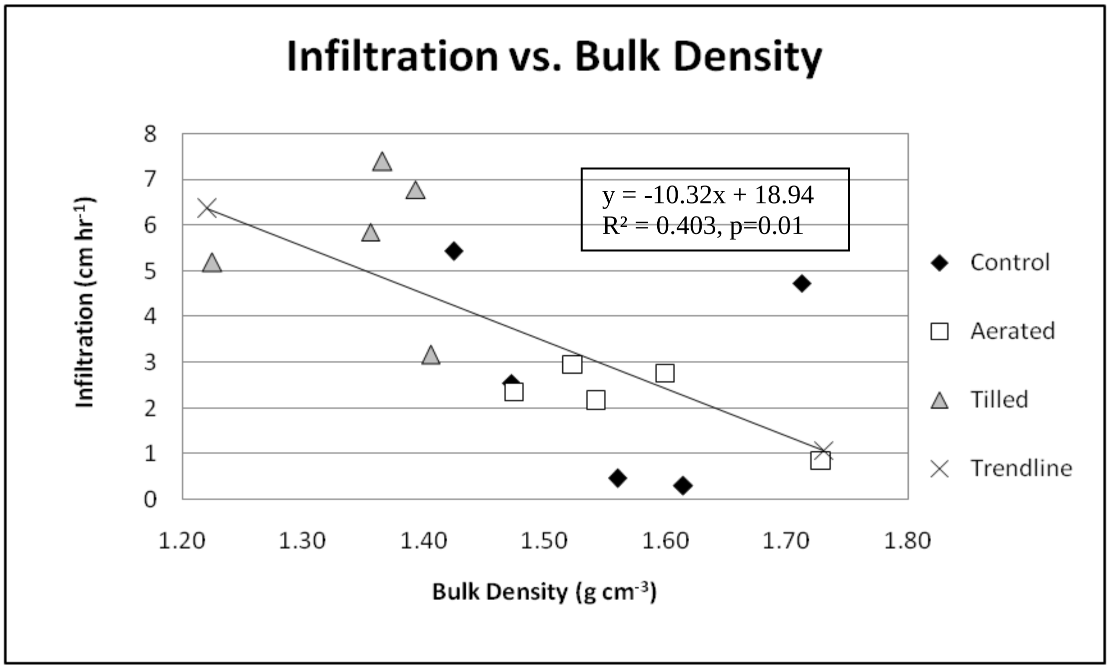


Figure 16. The relationship between bulk density and IR using the SR Method at Site 1.

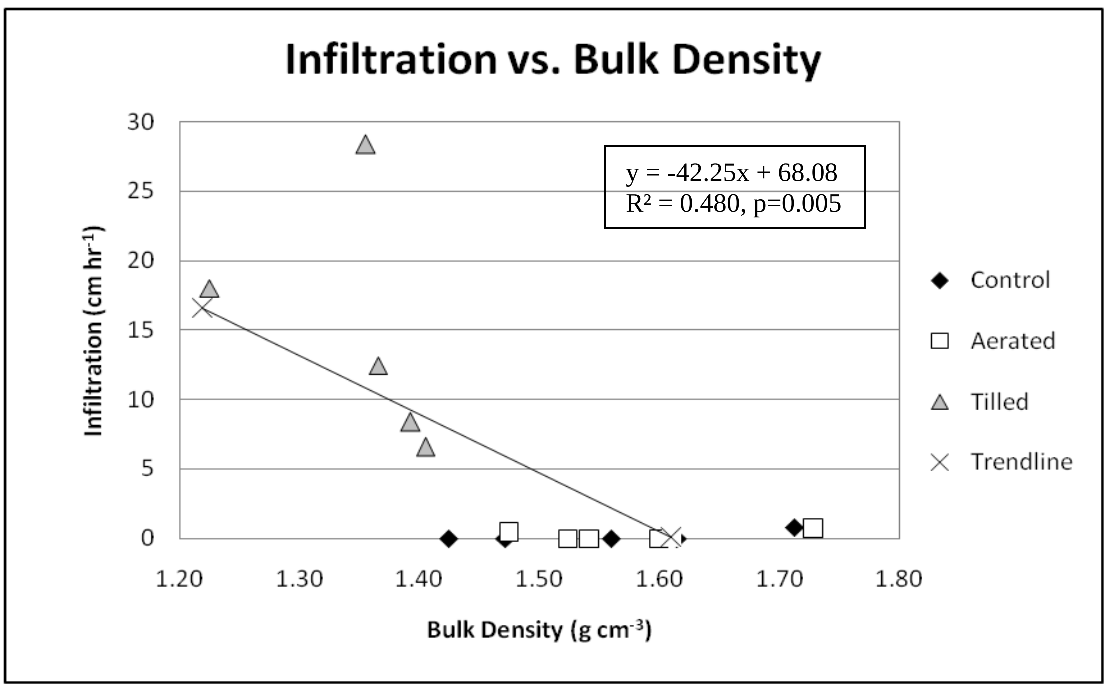


Figure 17. The relationship between bulk density and IR using the CSI method at Site 1.

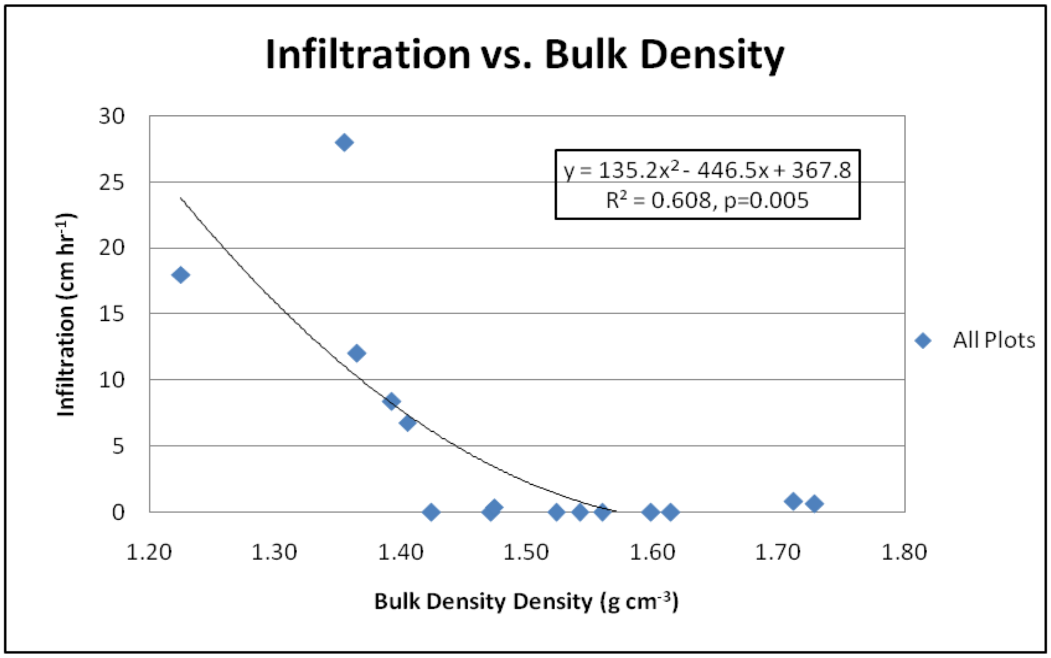


Figure 18. The relationship between bulk density and IR using the CSI method at Site 1 including a trendline.

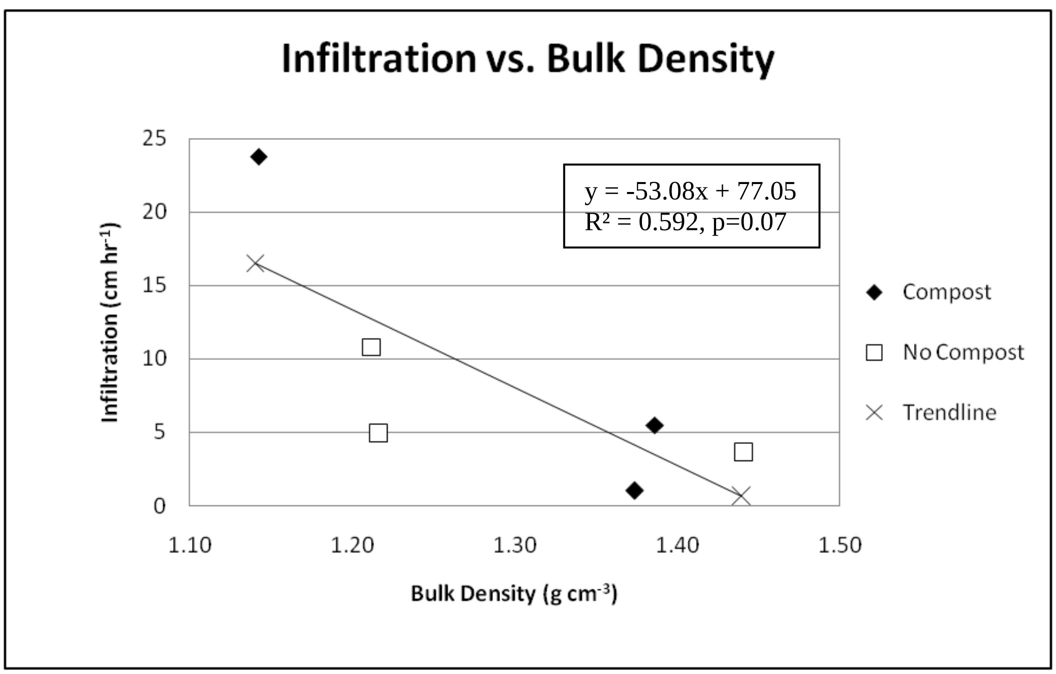


Figure 19. The relationship between bulk density and IR using the CSI method at Site 3.

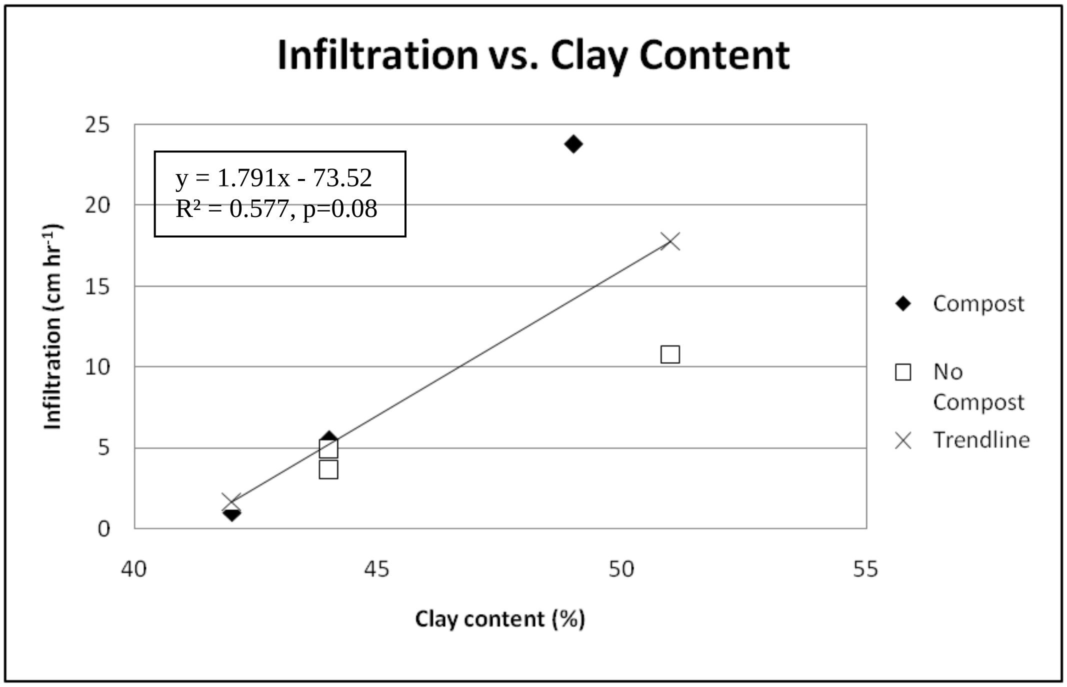


Figure 20. The relationship between clay content and IR using the CSI method at Site 3.

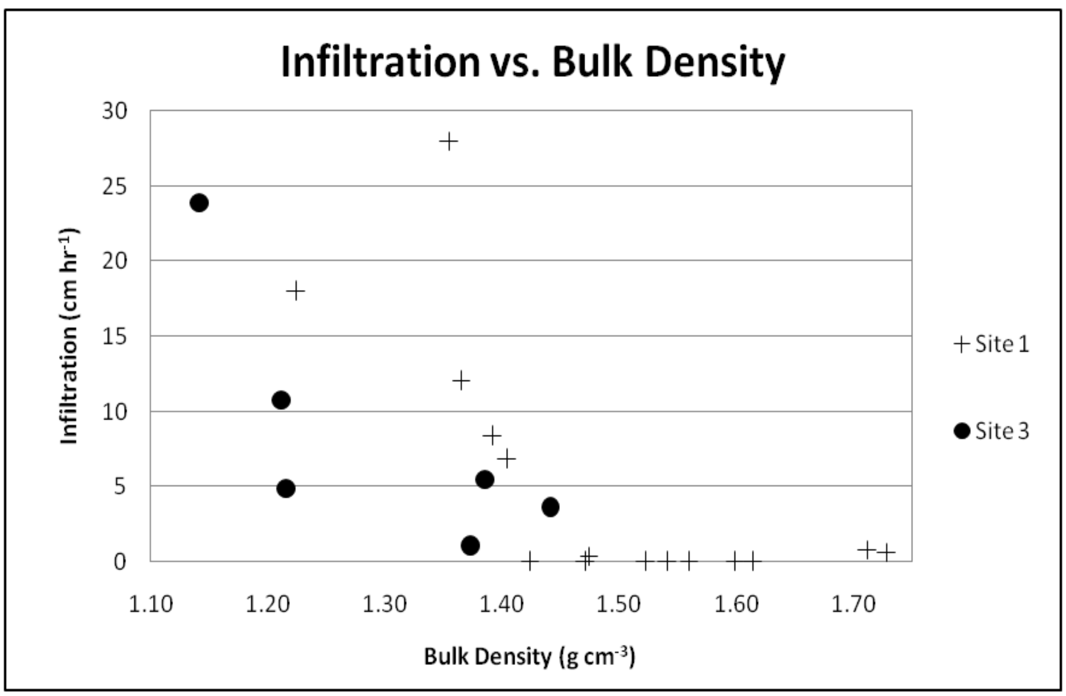


Figure 21. The relationship between bulk density and IR at Sites 1 and 3.

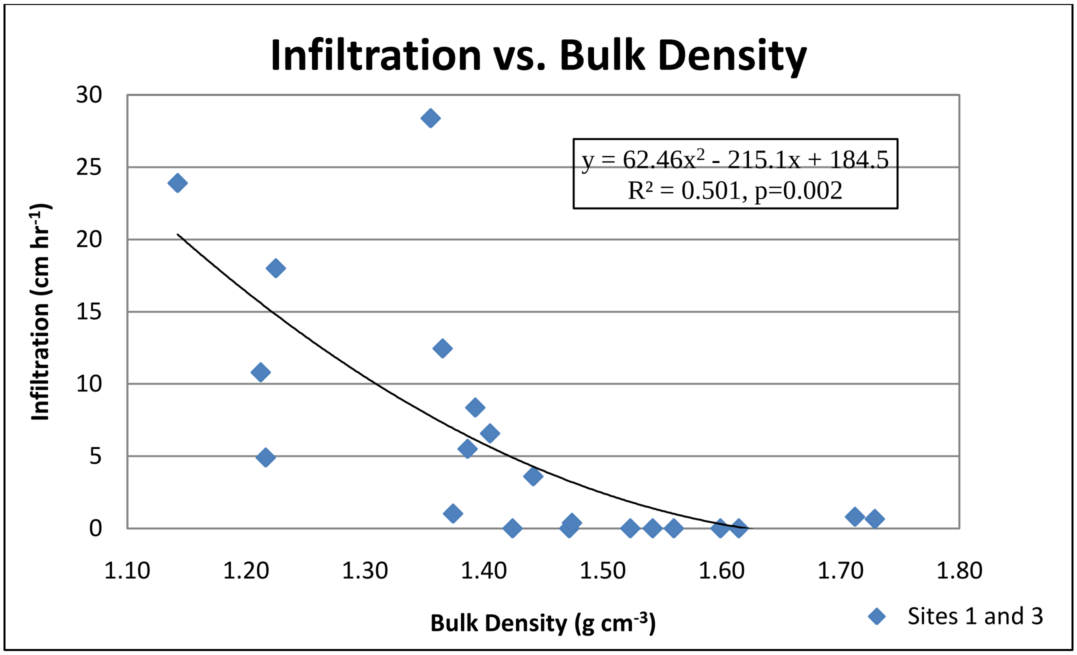


Figure 22. The relationship between bulk density and IR at Sites 1 and 3 including a trendline.

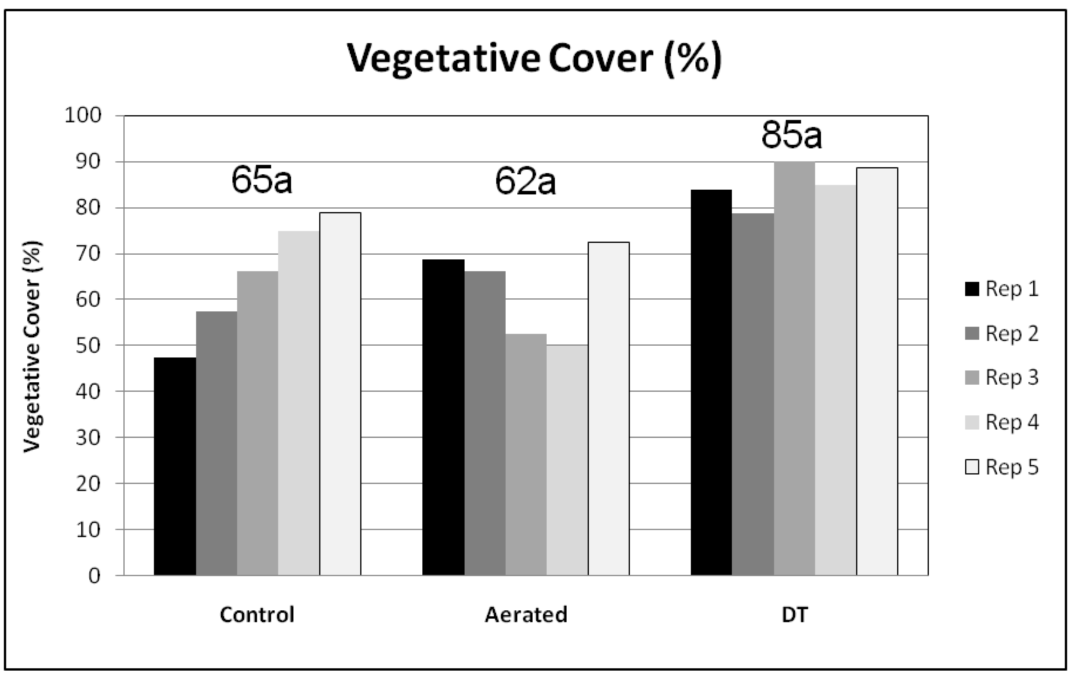


Figure 23. The percent vegetative cover at Site 1. Means followed by the same letter are not statistically different (p=0.05)

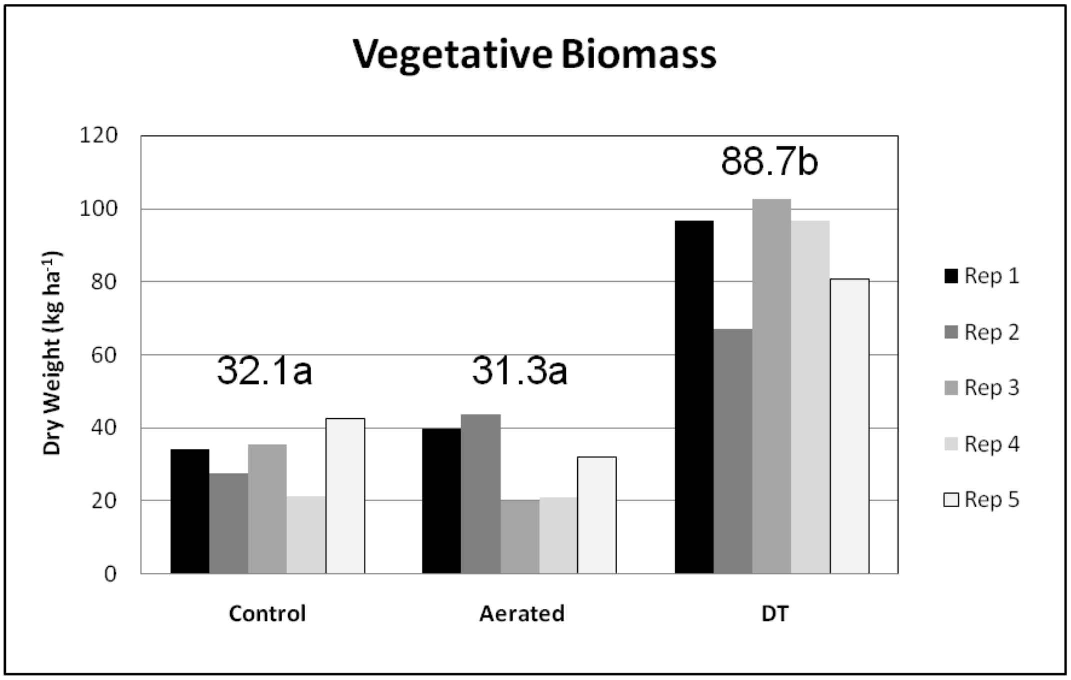


Figure 24. The above ground biomass at Site 1. Means followed by the same letter are not statistically different (p=0.002).

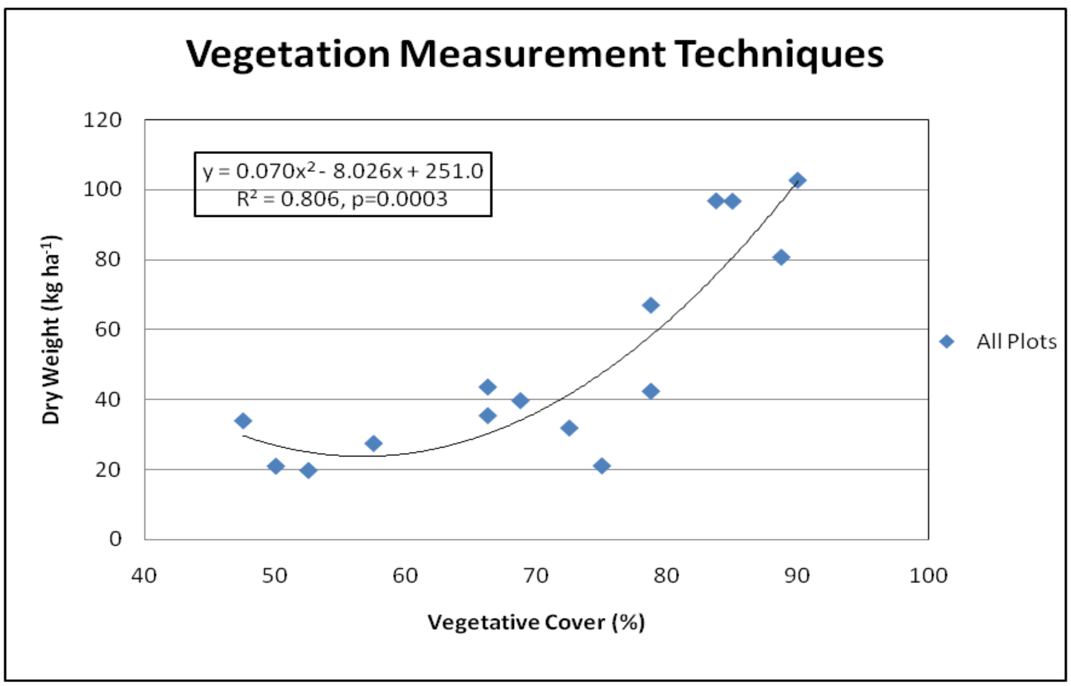


Figure 25. The relationship between dry weight and vegetative cover at Site 1.

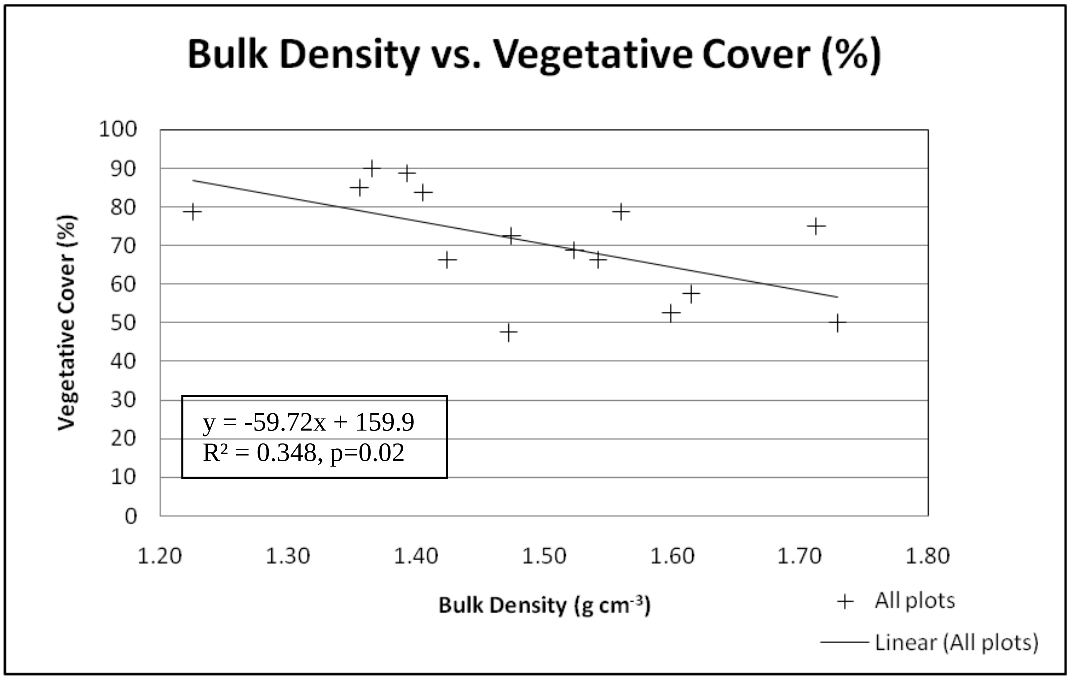


Figure 26. The relationship between bulk density and vegetative cover at Site 1.

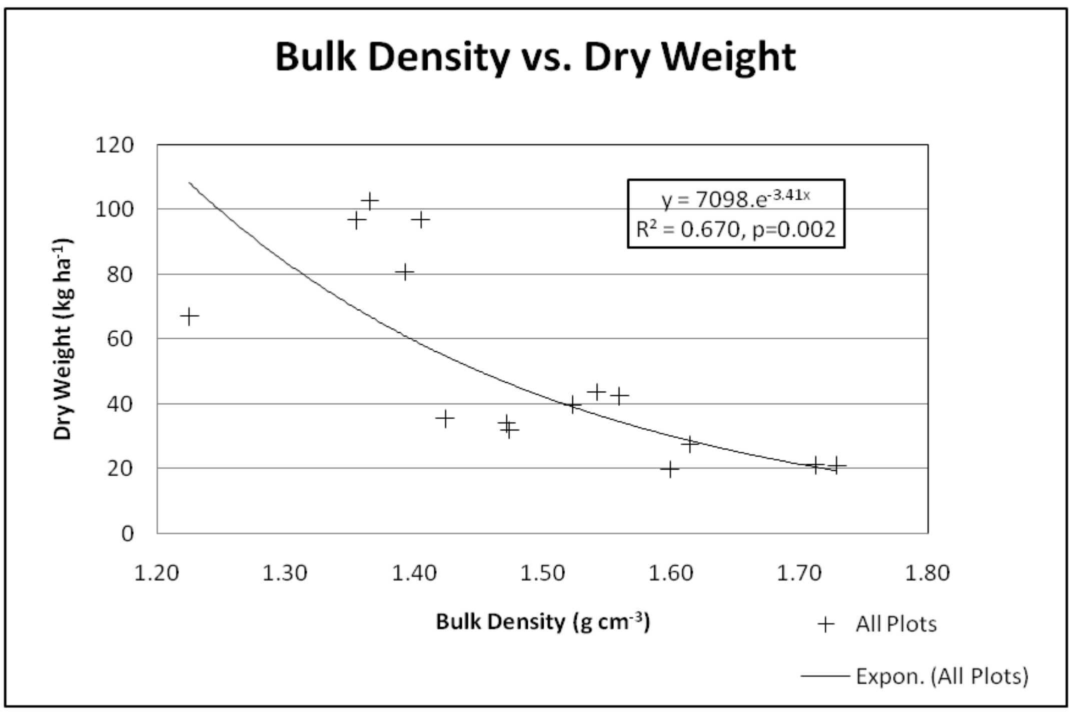


Figure 27. The relationship between bulk density and dry weight at Site 1.

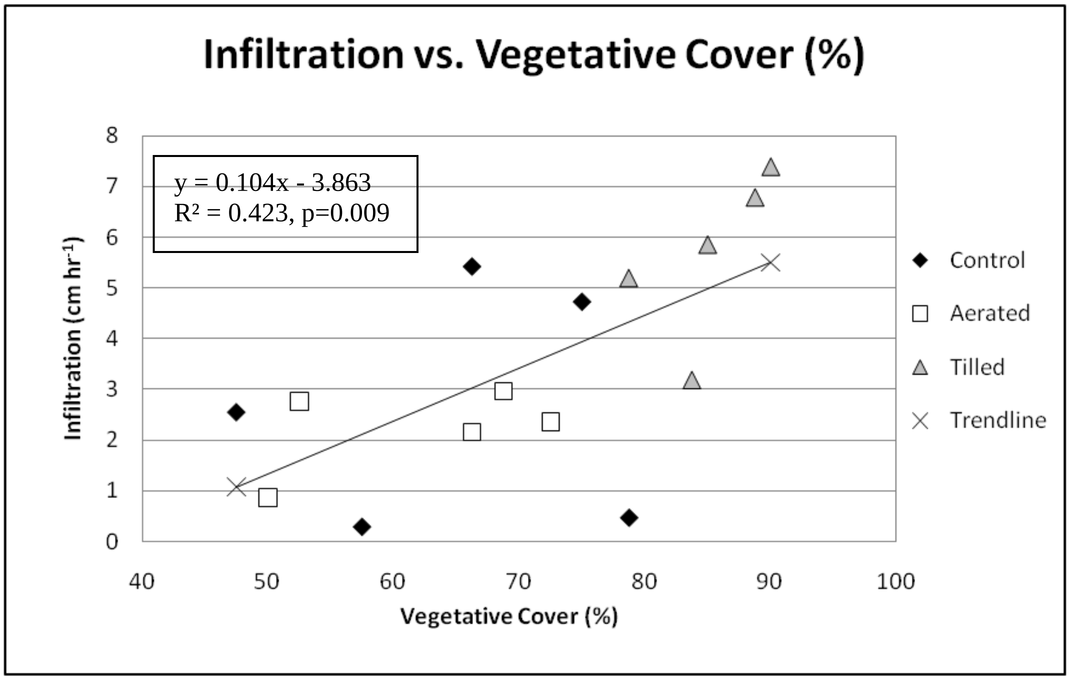


Figure 28. The relationship between percent coverage and IR using the SR method at Site 1.

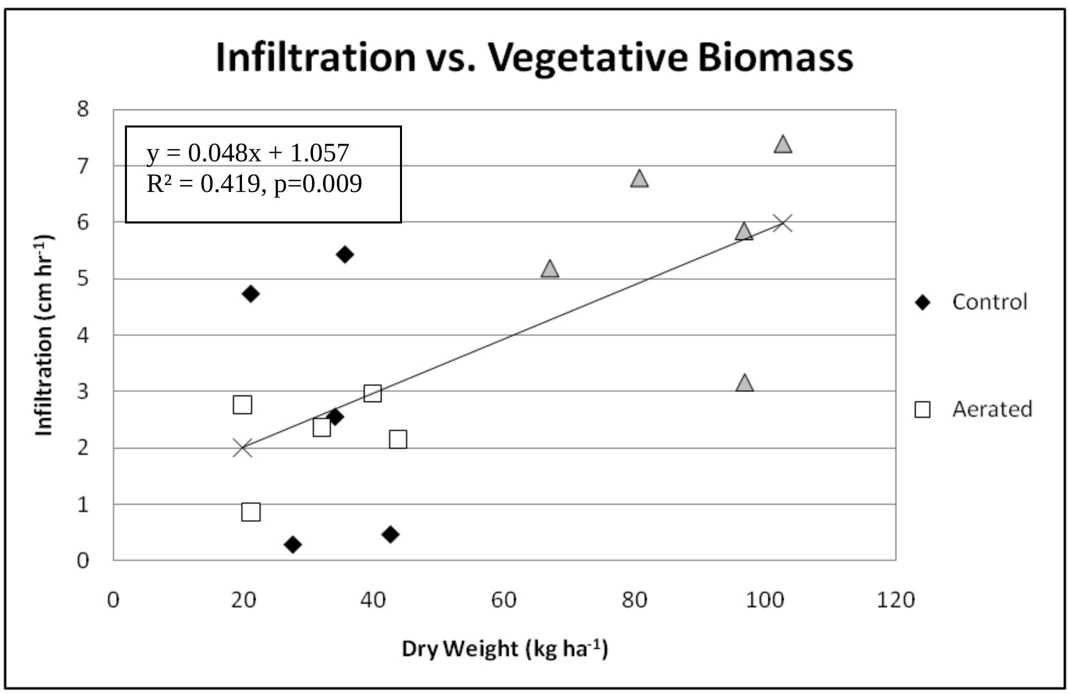


Figure 29. The relationship between dry weight and IR using the SR method at Site 1.

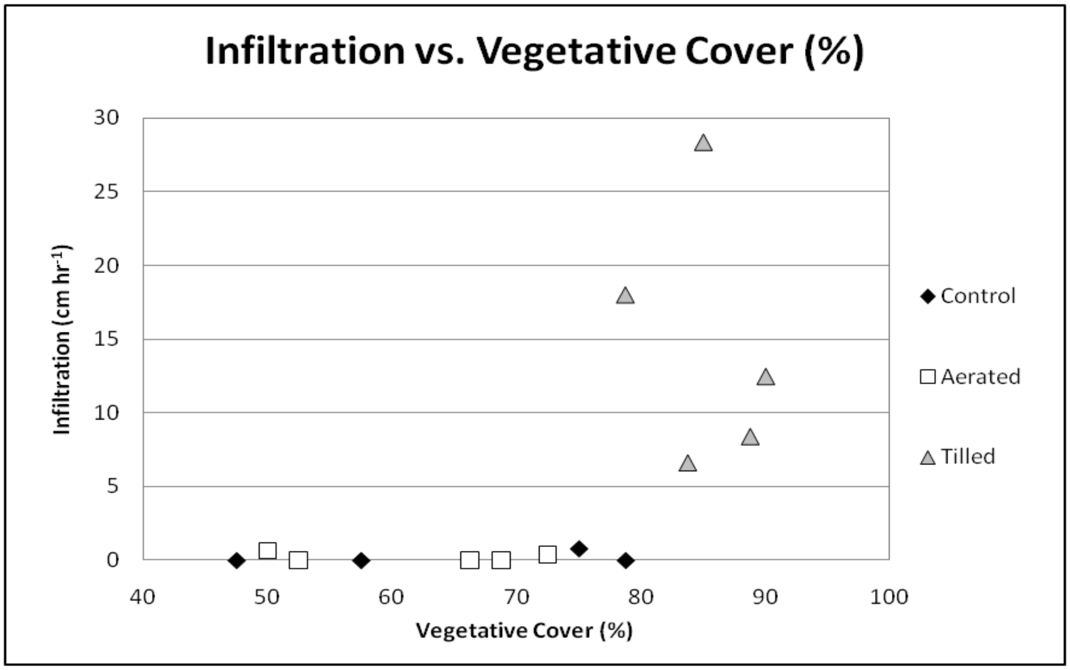


Figure 30. The relationship between percent coverage and IR using the CSI method at Site 1.

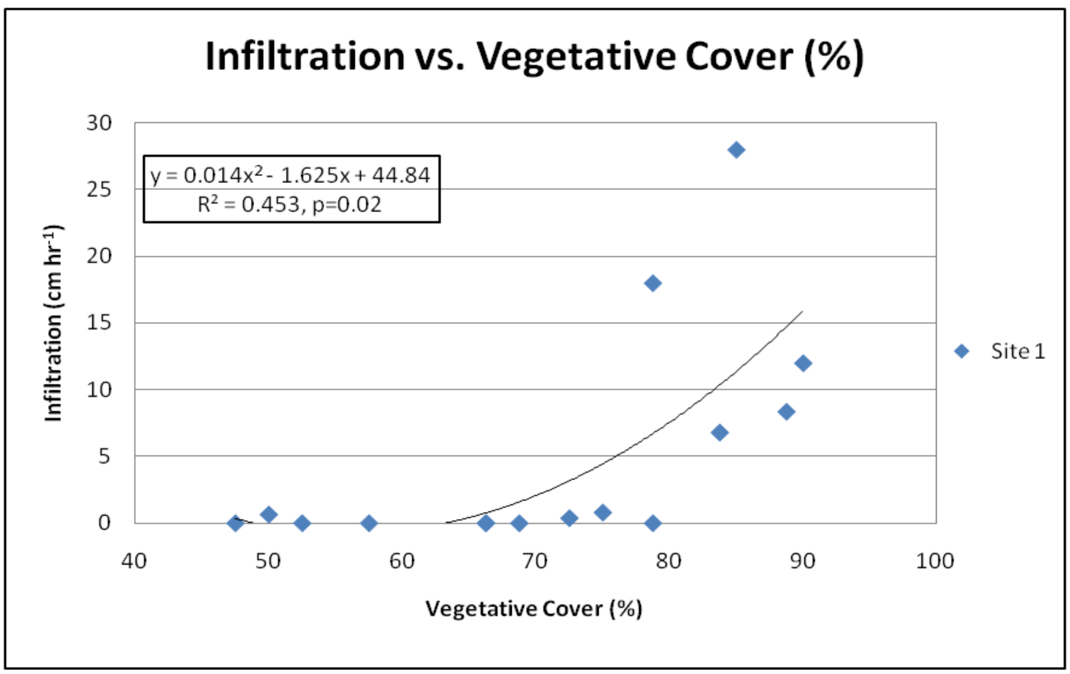


Figure 31. The relationship between percent coverage and IR using the CSI method at Site 1 including a trendline.

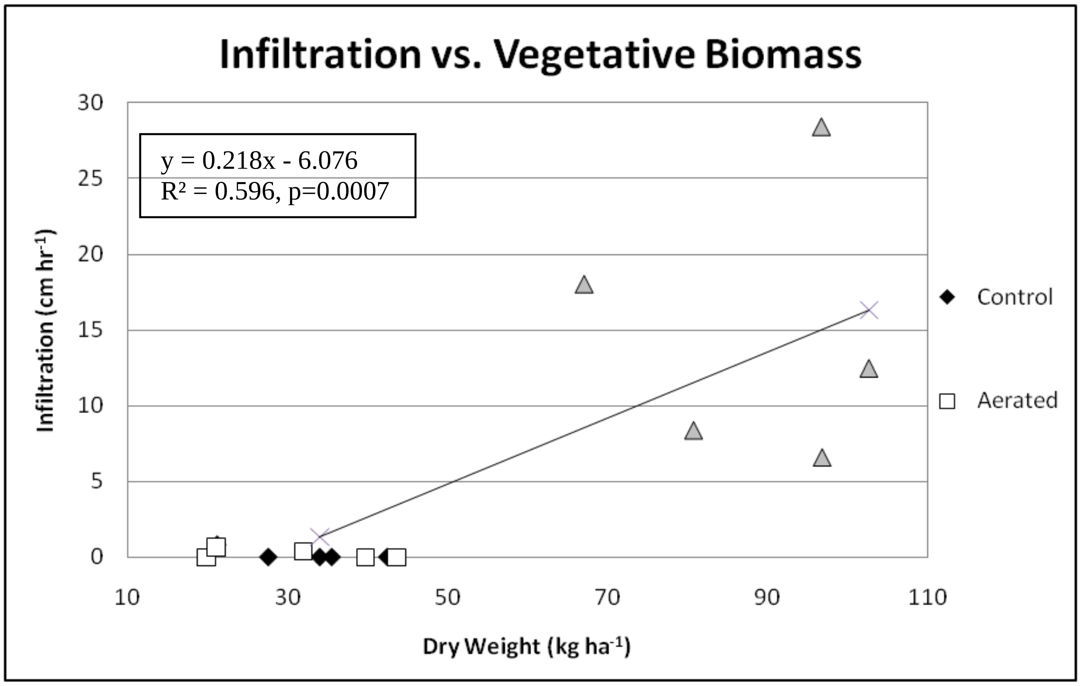


Figure 32. The relationship between dry weight and IR using the CSI method at Site 1.

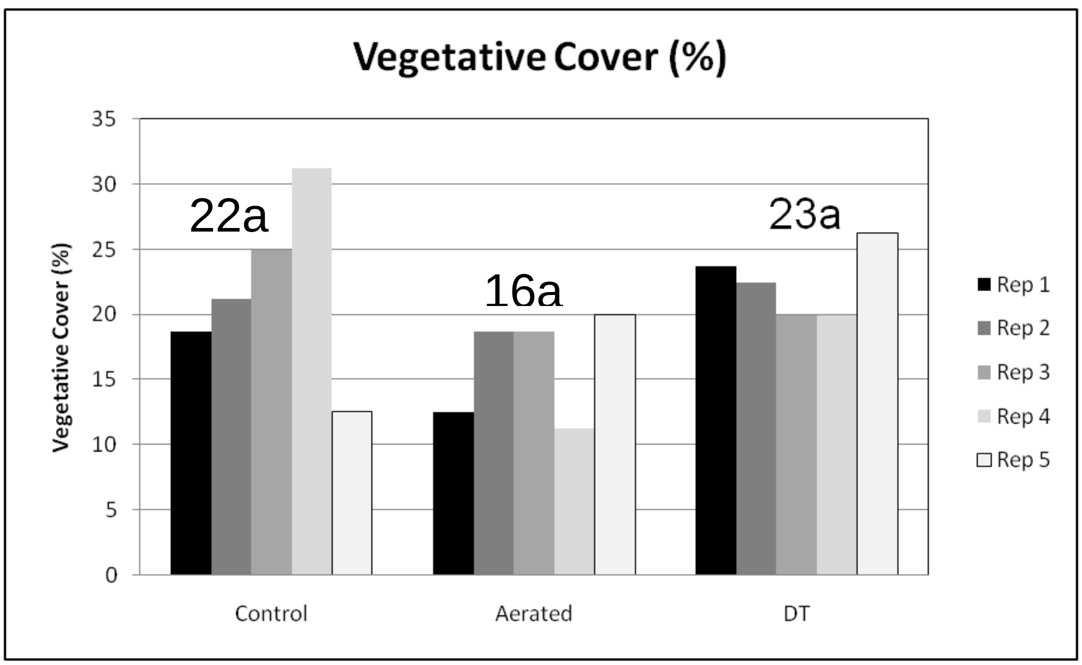


Figure 33. The percent vegetative coverage at Site 2.

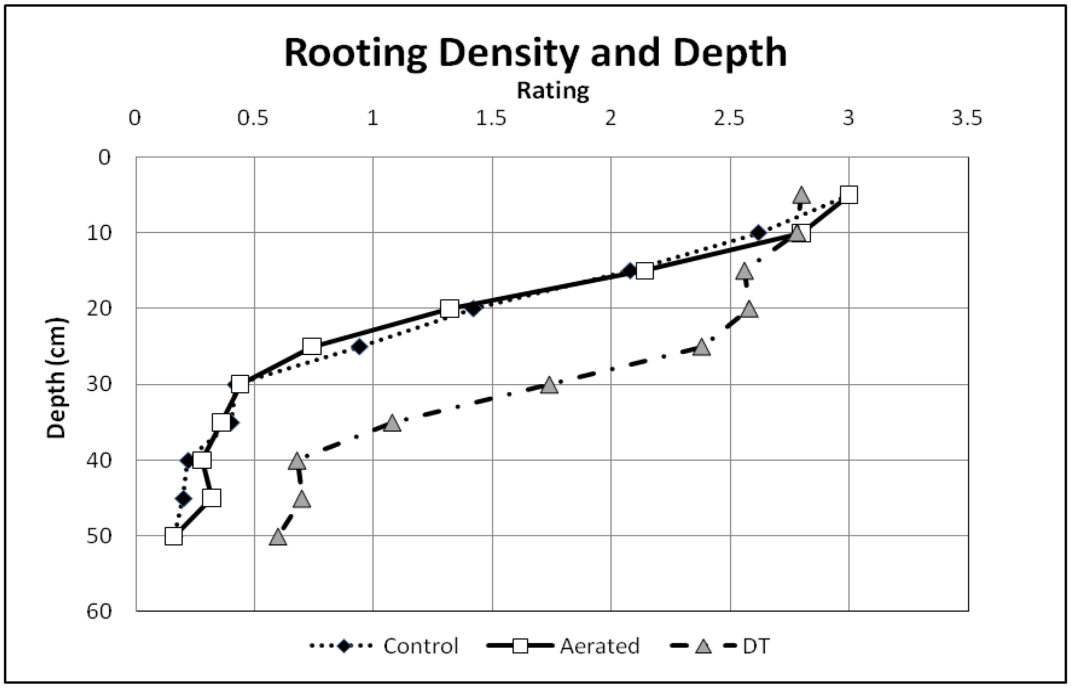


Figure 34. Root density data at each 5 cm increment, down to a depth of 50 cm.

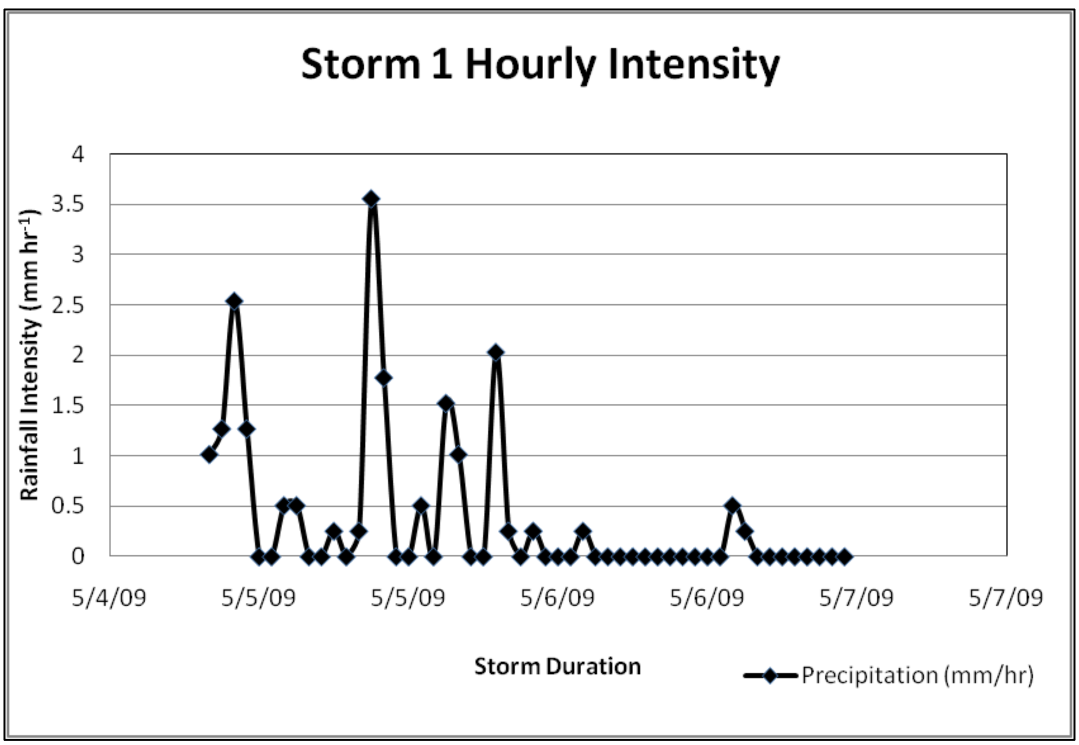


Figure 35. The hourly intensity of precipitation for Storm 1 (mm).

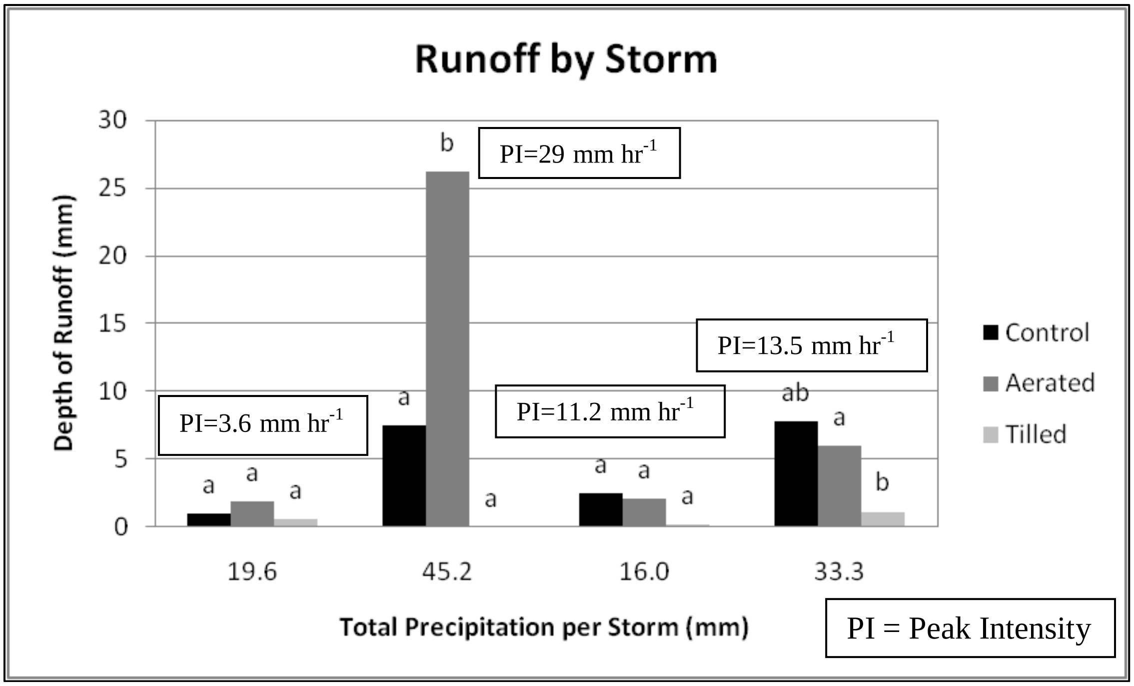


Figure 36. The average runoff amounts for each storm event. Means followed by the same letter are not statistically significant (p=0.07).

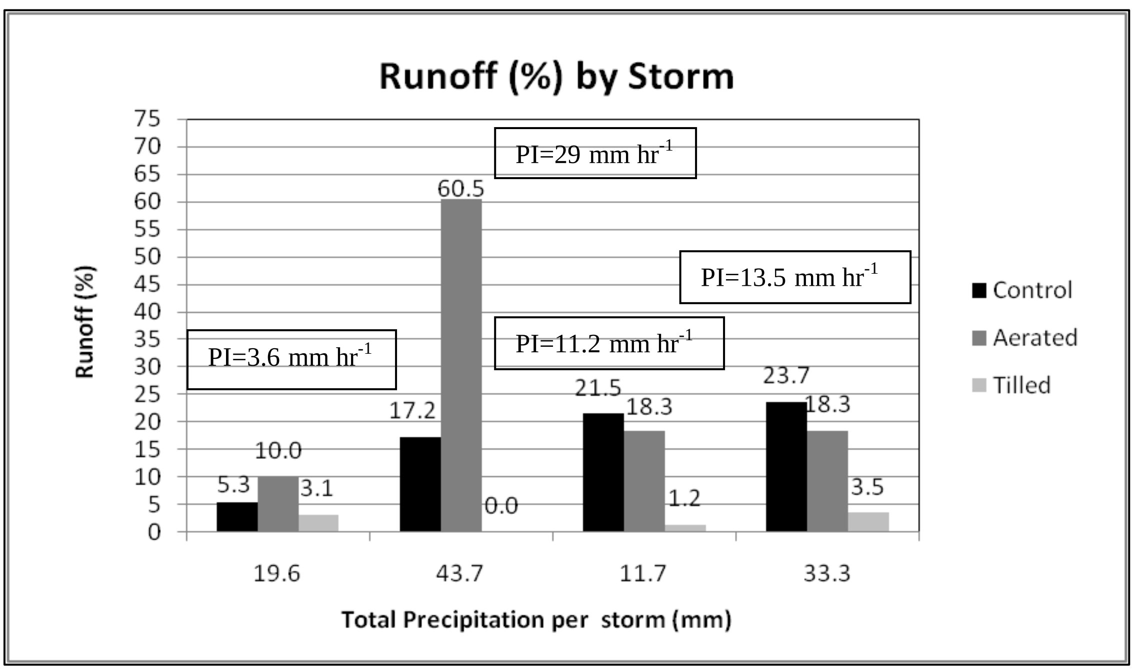


Figure 37. The average runoff (%) for each storm event. Means followed by the same letter are not statistically different (p=0.05)

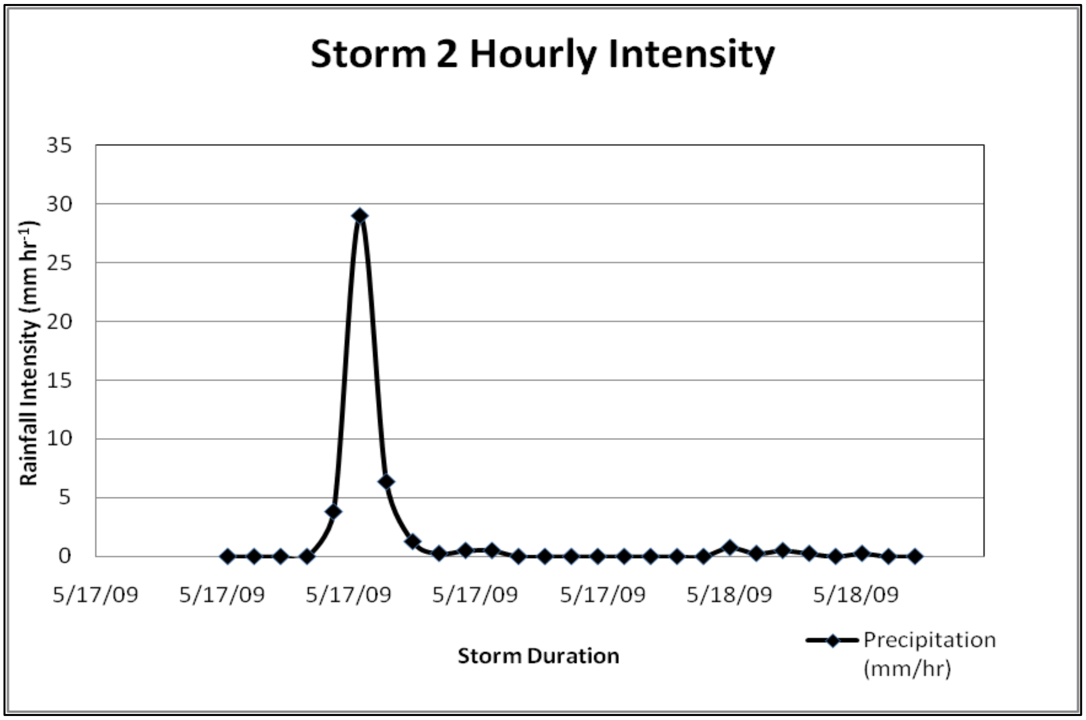


Figure 38. The hourly intensity of precipitation for Storm 2 (mm).

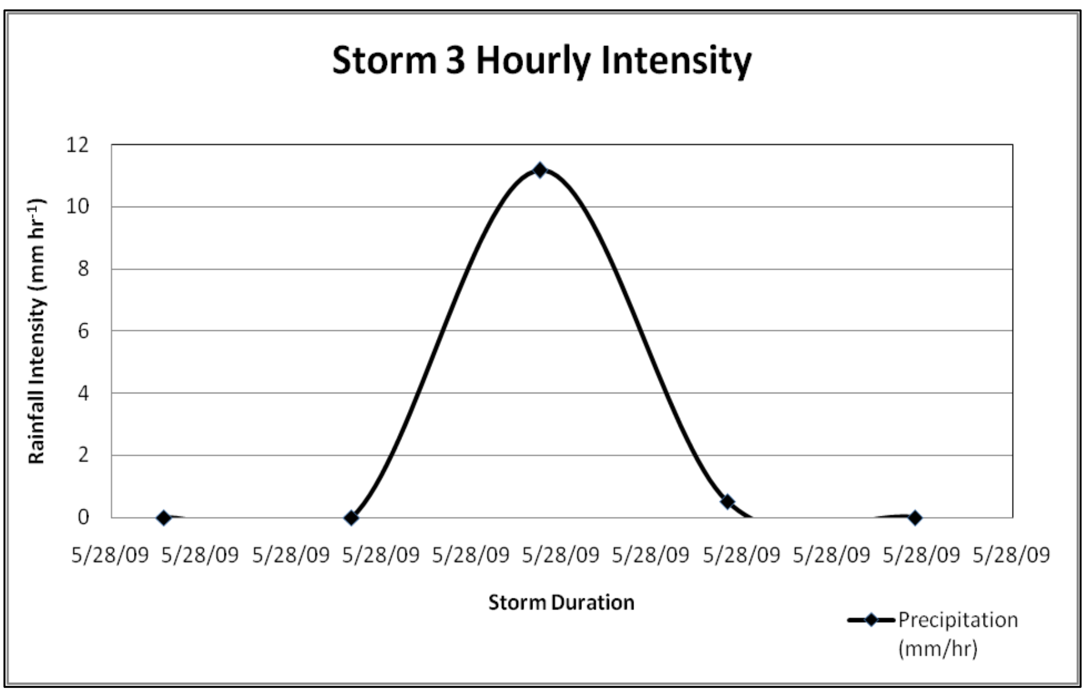


Figure 39. The hourly intensity of precipitation for Storm 3 (mm).

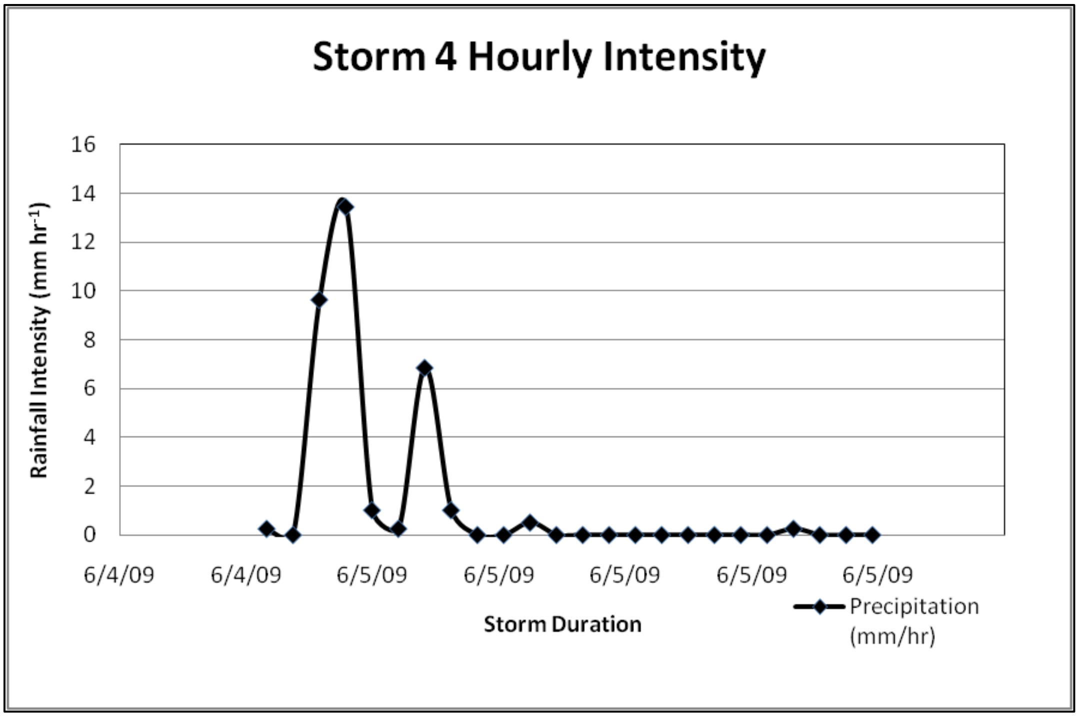


Figure 40. The hourly intensity of precipitation for Storm 4 (mm).

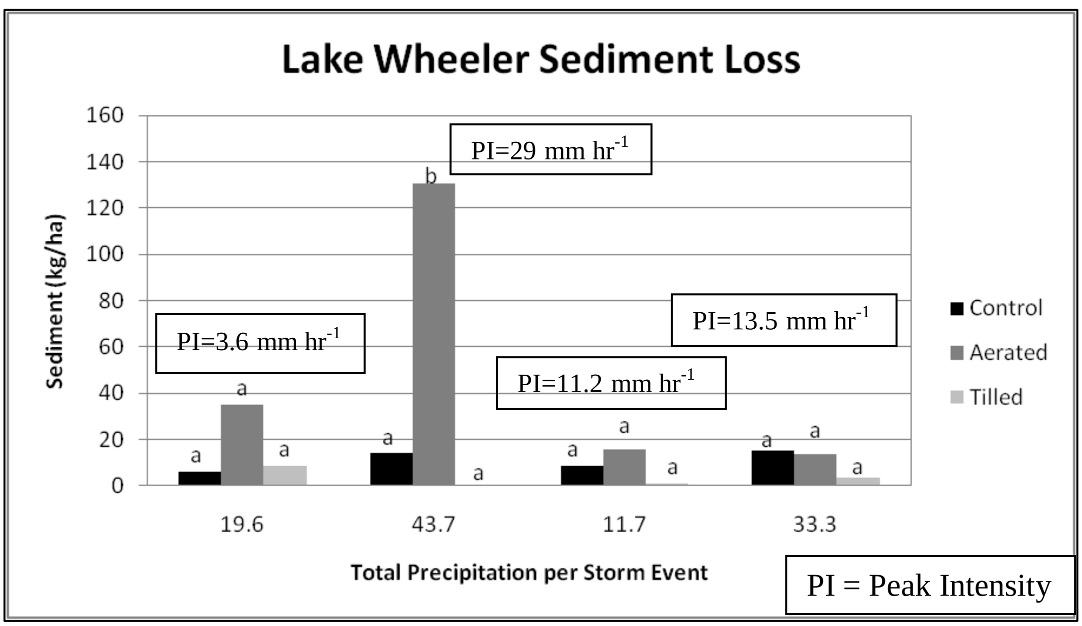
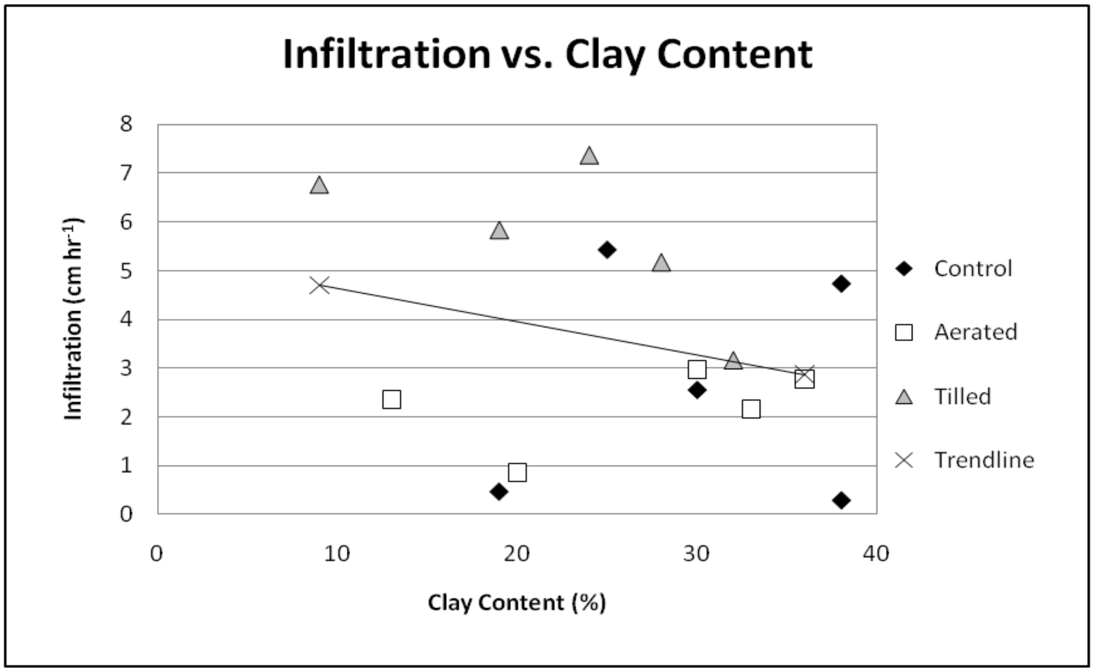


Figure 41. Sediment losses for the four storm events. Means followed by the same letter are not statistically significant (p=0.05).

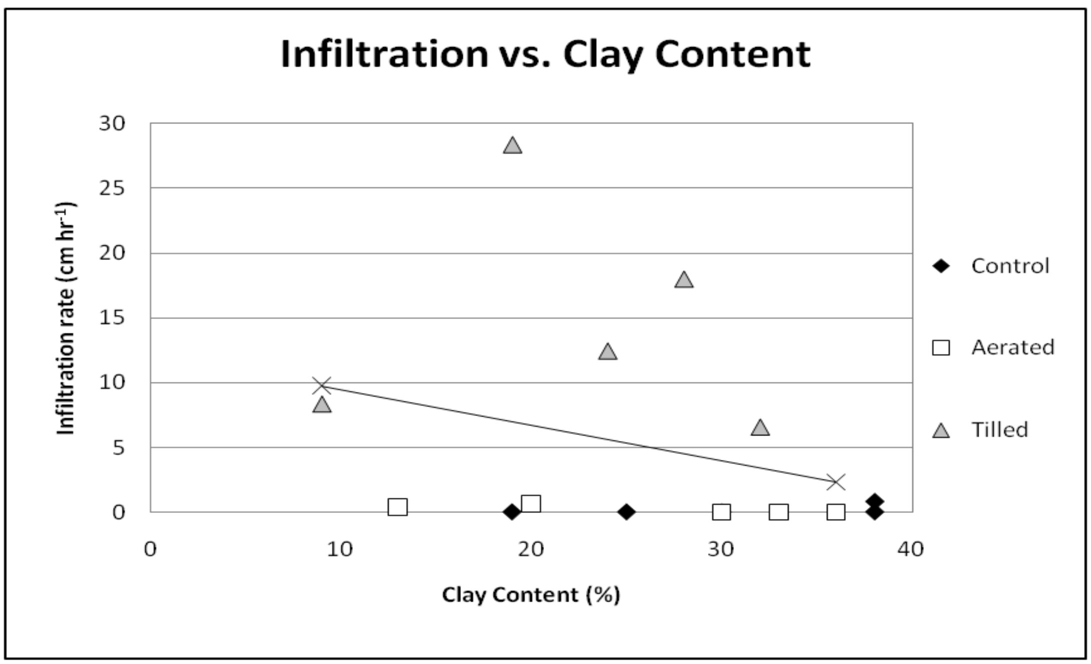
APPENDICES

Appendix 1-a. Rating system for root analysis. Each grid was analyzed at 5 cm increments down to a depth of 50 cm. Each replication was measured and combined for the average of each treatment, as shown above.

	Rating					
Depth(cm)	Rep1	Rep2	Rep3	Rep4	Rep5	Average
5	3	3	3	3	3	3
10	3	2.1	3	2	3	2.62
15	2.1	2	2.7	1.6	2	2.08
20	1.2	2	1.2	1.4	1.3	1.42
25	0.6	1.6	0.5	1.1	0.9	0.94
30	0.4	0.3	0.4	0.5	0.5	0.42
35	0.6	0.2	0.4	0.5	0.3	0.4
40	0.3	0.1	0.4	0.3	0	0.22
45	0.1	0.1	0.4	0.4	0	0.2
50	0.4	0	0.1	0.3	0	0.16



Appendix 1-b. The relationship between clay content and IR using the SR method for Site 1.



Appendix 1-c. The relationship between clay content and IR using the CSI method for Site 1.

Appendix 1-d. Particle Size data for Site 1.

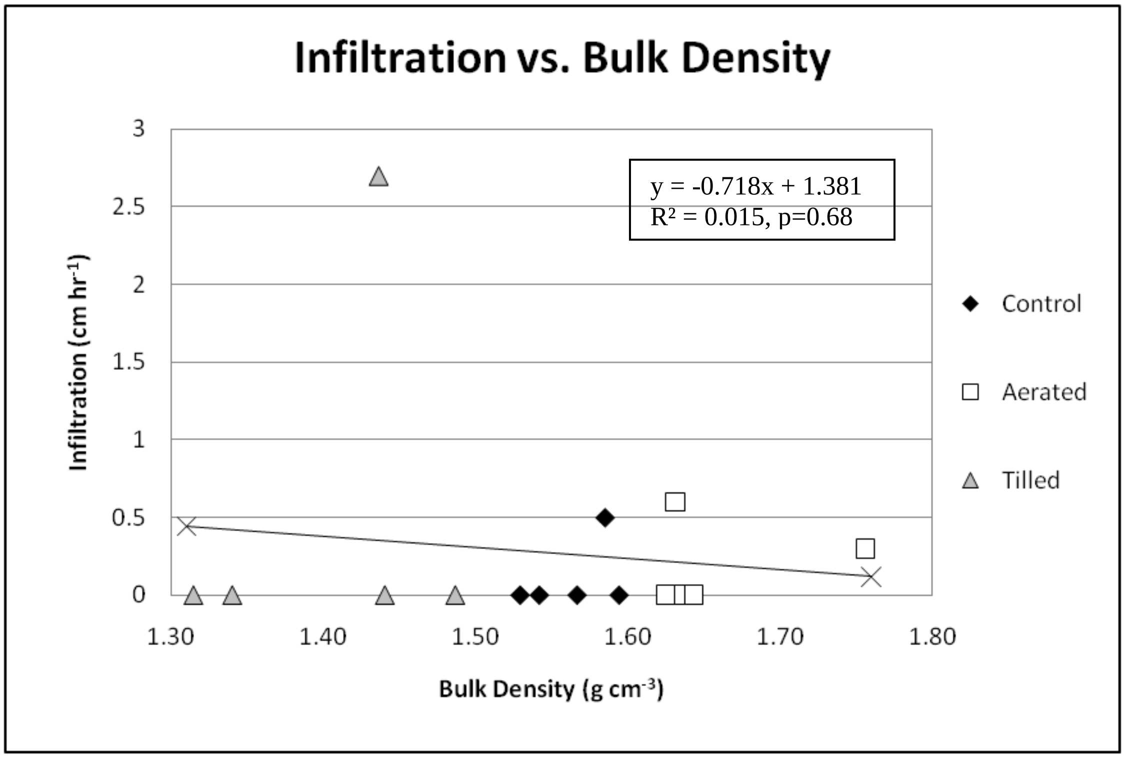
Treatment	Particle Size Fractions		
	Sand	Silt	Clay
Control	40	30	30
Tilled	40	28	32
Aerated	38	32	30
Tilled	46	26	28
Control	42	19	38
Aerated	40	27	33
Aerated	43	21	36
Control	52	23	25
Tilled	59	17	24
Control	42	20	38
Tilled	64	17	19
Aerated	62	18	20
Aerated	70	17	13
Tilled	74	17	9
Control	63	18	19
AVERAGE	**53**	**21**	**26**

Appendix 1-e. Particle Size date for Site 2.

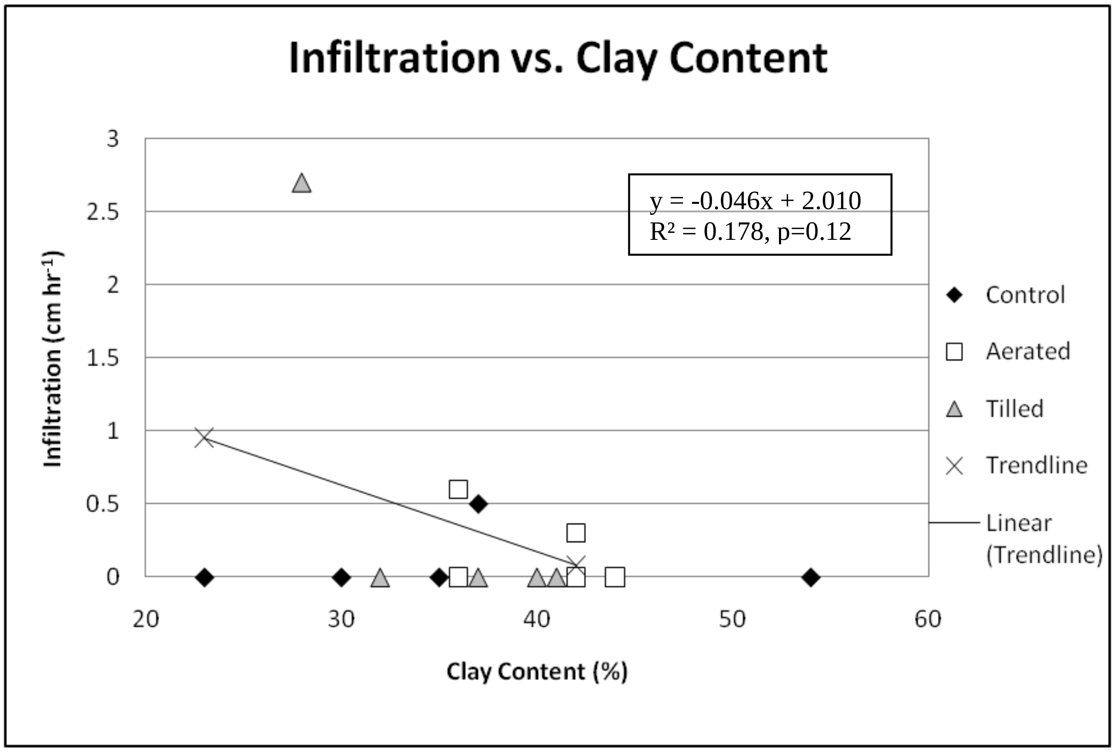
Treatment	Particle Size Fractions		
	Sand	Silt	Clay
Control	42	23	35
Tilled	49	23	28
Aerated	46	18	36
Tilled	47	21	32
Control	46	21	33
Aerated	44	14	42
Aerated	44	20	36
Control	52	18	30
Tilled	46	17	37
Control	46	17	37
Tilled	41	18	41
Aerated	41	15	44
Aerated	36	22	42
Tilled	34	26	40
Control	30	16	54
AVERAGE	**43**	**19**	**38**

Appendix 1-f. General summary of site chracteristics.

	Site 1	Site 2	Site 3
Planting Date	April 27th, 2009	October 22, 2009	January 26th, 2009
Slope	3%	0.5%	0.5%
Treatments	C, A, and DT	C, A, and DT	CT and DT
Soil Texture	CL, SCL, SL	CL, SCL, C	C



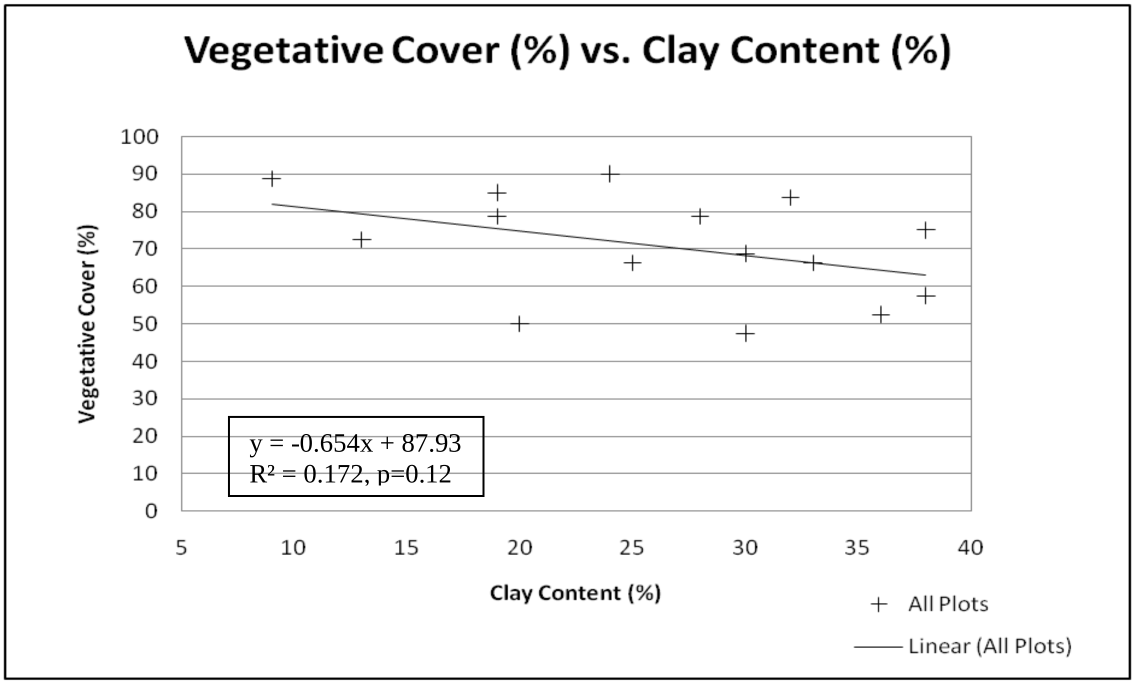
Appendix 1-g. The relationship between bulk density and IR using the CSI method for Site 2.



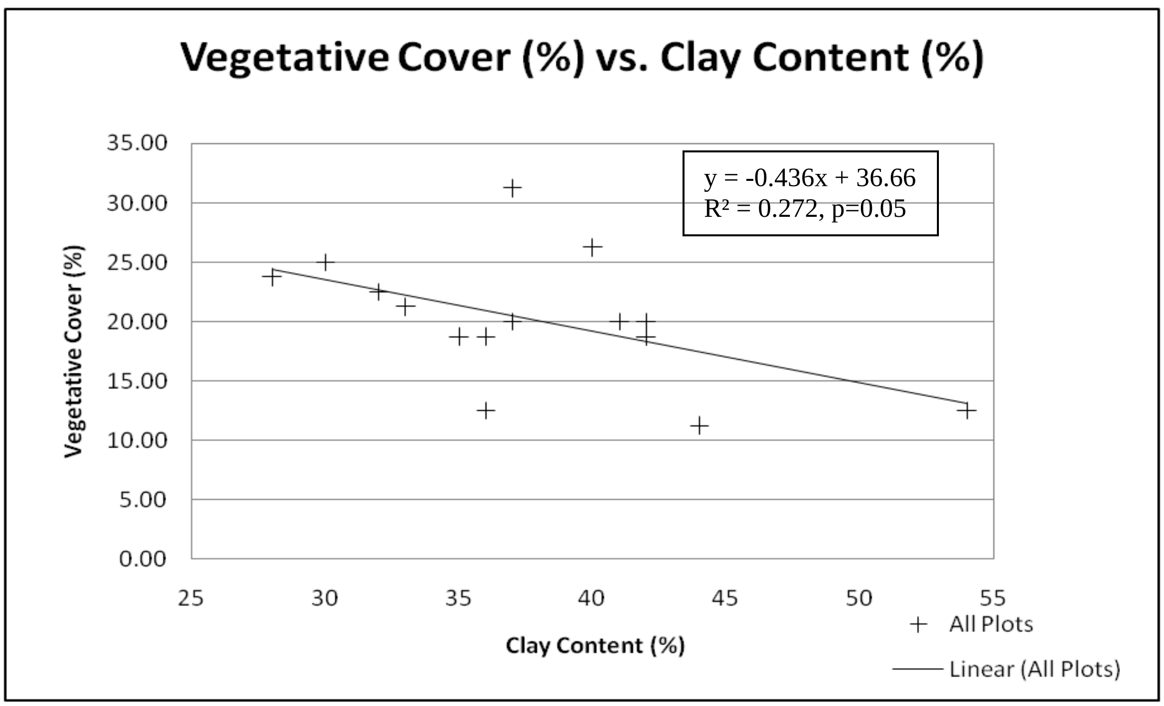
Appendix 1-h. The relationship between clay content and IR using the CSI method for Site 2.

Appendix 1-i. Particle Size data for Site 3.

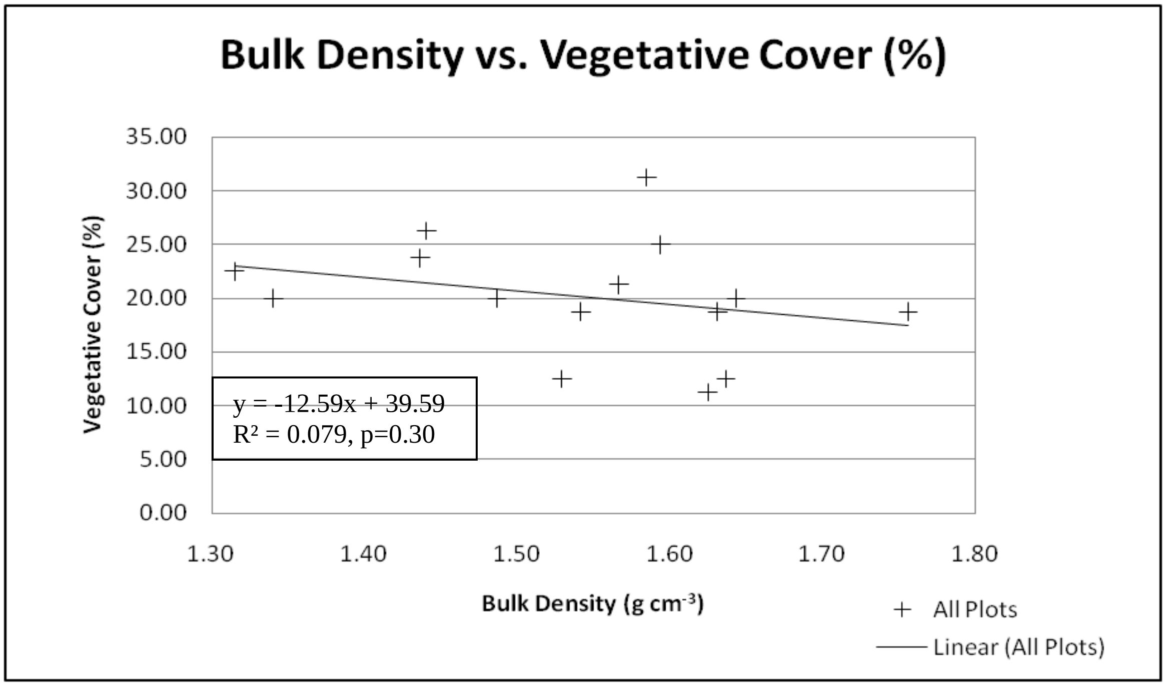
Treatment	Particle Size Fractions		
	Sand	Silt	Clay
CT	38	20	42
CT	39	17	44
DT	41	15	44
DT	39	17	44
DT	33	16	51
CT	36	15	49
AVERAGE	**38**	**16**	**46**



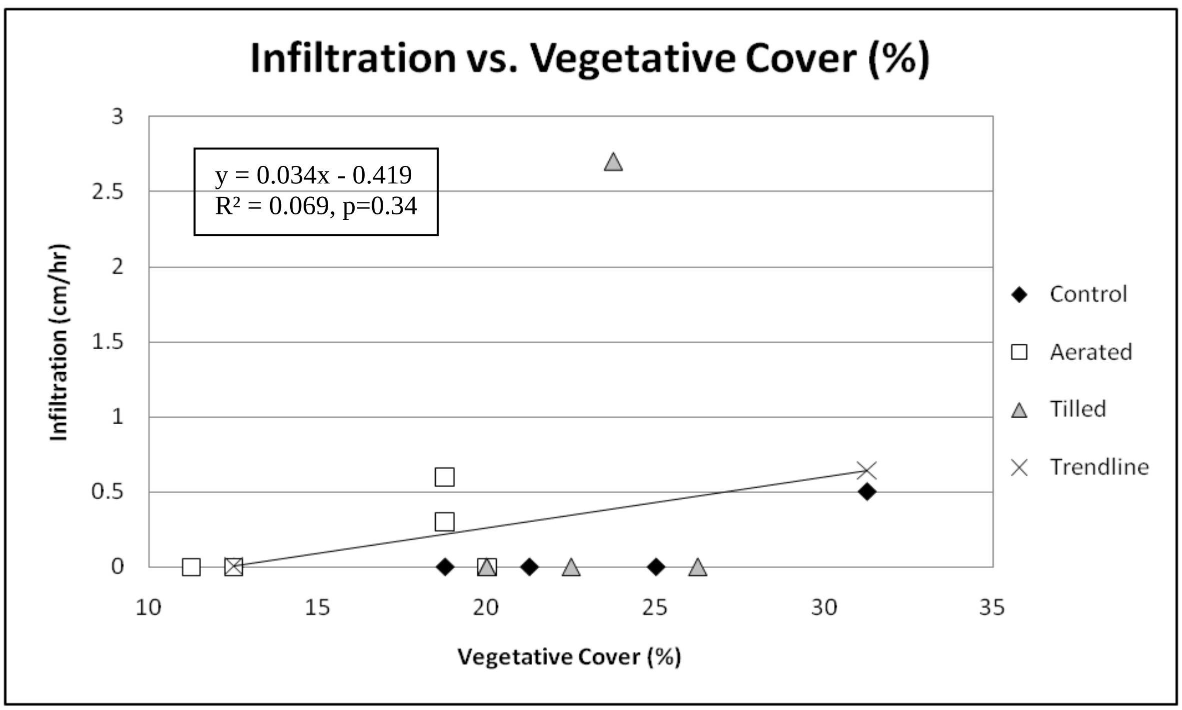
Appendix 1-j. The relationship between vegetative cover and clay content at Site 1.



Appendix 1-k. The relationship between percent coverage and clay content at Site 2.



Appendix 1-l. The relationship between percent coverage and bulk density at Site 2.



Appendix 1-m. The relationship between percent cover and IR using the CSI method at Site 2.

Appendix 2. Example SAS input and output for Stormwater/Sediment Loss data

```
**Reapeated2B.sas;

**newdata on July8th,2010;
title "Using All Data";

options formdlim='_' pageno=1;
data a;
 infile 'stormData.csv' dlm=',' dsd missover firstobs=2;
 input storm trt $ rainfall runoff SedLoss rep;

/*proc print data=a; run;*/

 run;


proc sort data=a; by rep trt storm; ** storm at the end;

ods rtf file="Repeated2B.rtf" style=Journal;

ods graphics on;
ods listing close;
ods trace on;

%macro rr(var);

ods exclude residualpanel pearsonPanel diffs;
proc mixed data=a /*plots=studentpanel*/;

  class rep trt storm;
  model  &var =storm trt storm*trt/ residual ddfm=kr;
  random rep rep*trt;
  repeated/ sub=rep*trt  group=trt;
  lsmeans trt*storm / pdiff slice=storm;
  ods output  diffs=diffs;
  Title2 " &var";

  proc sort data=diffs; by storm _trt;
  proc print data=diffs; where storm=_storm;** diff within each storm; by
storm;

run;quit;
%mend rr;

%rr(sedloss)
%rr(runoff)

ods graphics off;
ods rtf close;
ods trace off;
ods listing
```

Example SAS output

Sediment Loss

Model Information	
Data Set	WORK.A
Dependent Variable	SedLoss
Covariance Structure	Variance Components
Subject Effect	rep*trt
Group Effect	trt
Estimation Method	REML
Residual Variance Method	None
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information

Class	*Levels*	*Values*
rep	5	1 2 3 4 5
trt	3	Aerated Control Tilled
storm	4	1 2 3 4

Dimensions	
Covariance Parameters	5
Columns in X	20
Columns in Z	20
Subjects	1
Max Obs Per Subject	60

Number of Observations	
Number of Observations Read	60
Number of Observations Used	60
Number of Observations Not Used	0

Iteration History			
Iteration	*Evaluations*	*-2 Res Log Like*	*Criterion*
0	1	319.65801841	
1	4	306.46855933	0.00214364
2	3	302.37553895	0.00241133
3	1	293.93248390	0.00664243
4	1	284.49882189	0.02166188
5	1	276.72489727	0.04905111
6	1	272.28020287	0.00420940
7	1	272.07699638	.
8	1	271.97976468	.
9	1	271.90868191	0.00004624
10	1	271.90420561	0.00000035
11	1	271.90417310	0.00000000

Convergence criteria met.

Covariance Parameter Estimates			
Cov Parm	*Subject*	*Group*	*Estimate*
rep			0
*rep*trt*			0.07295
Residual	rep*trt	trt Aerated	75.2131
Residual	rep*trt	trt Control	14.9541
Residual	rep*trt	trt Tilled	1.2069

Fit Statistics	
-2 Res Log Likelihood	271.9
AIC (smaller is better)	279.9
AICC (smaller is better)	280.8
BIC (smaller is better)	278.3

Type 3 Tests of Fixed Effects

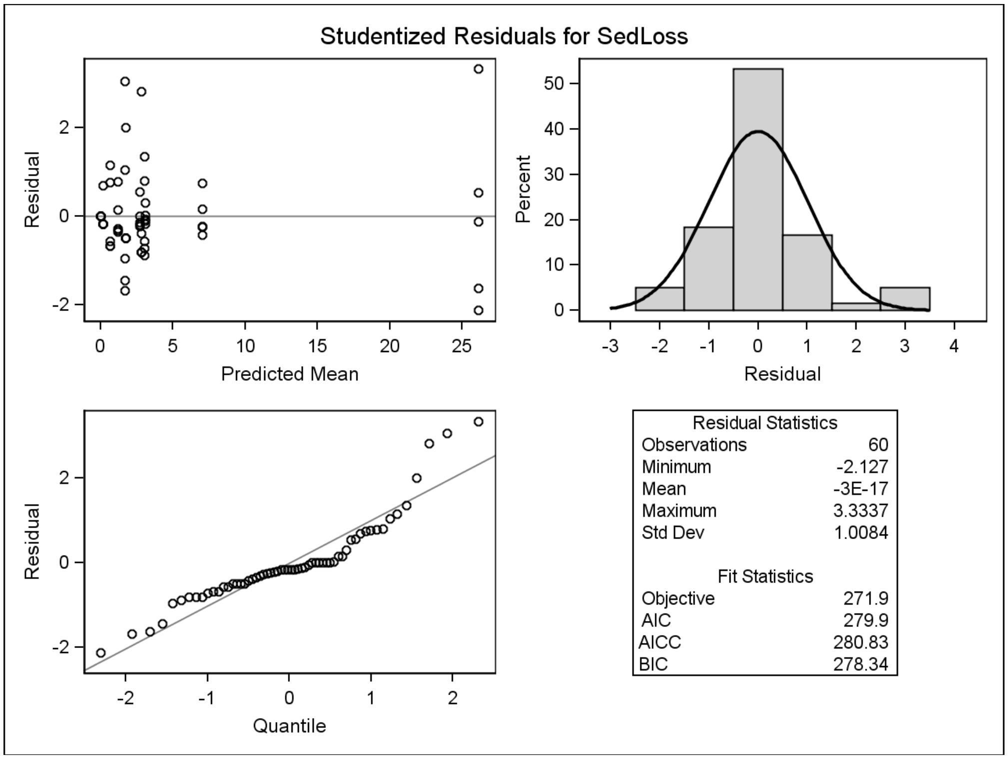
Effect	*Num DF*	*Den DF*	*F Value*	*Pr > F*
storm	3	22.6	6.74	0.0020
trt	2	21.9	11.56	0.0004
*trt*storm*	6	25.2	4.39	0.0036

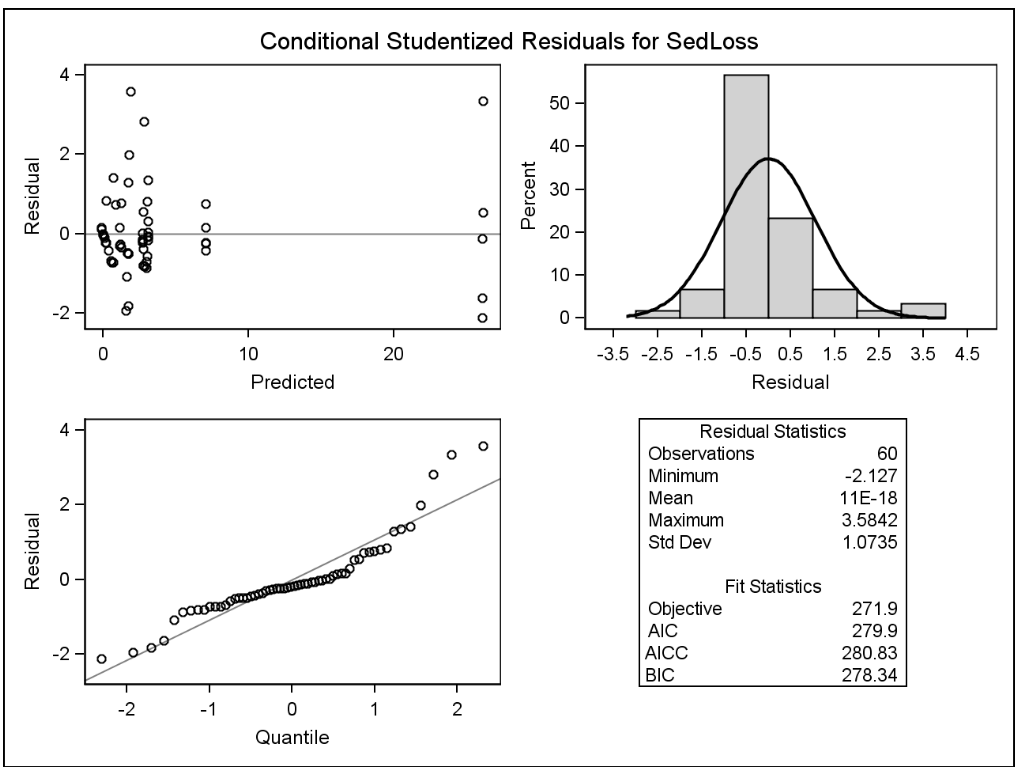
Least Squares Means

Effect	*trt*	*storm*	*Estimate*	*Standard Error*	*DF*	*t Value*	*Pr > |t|*
*trt*storm*	Aerated	1	7.0545	3.8804	16	1.82	0.0878
*trt*storm*	Aerated	2	26.1280	3.8804	16	6.73	<.0001
*trt*storm*	Aerated	3	3.0900	3.8804	16	0.80	0.4375
*trt*storm*	Aerated	4	2.7160	3.8804	16	0.70	0.4940
*trt*storm*	Control	1	1.1940	1.7336	16	0.69	0.5009
*trt*storm*	Control	2	2.8060	1.7336	16	1.62	0.1251
*trt*storm*	Control	3	1.7300	1.7336	16	1.00	0.3332
*trt*storm*	Control	4	3.0360	1.7336	16	1.75	0.0991
*trt*storm*	Tilled	1	1.7040	0.5059	15.8	3.37	0.0040
*trt*storm*	Tilled	2	2.22E-16	0.5059	15.8	0.00	1.0000
*trt*storm*	Tilled	3	0.1743	0.5059	15.8	0.34	0.7350
*trt*storm*	Tilled	4	0.6820	0.5059	15.8	1.35	0.1967

Tests of Effect Slices

Effect	*storm*	*Num DF*	*Den DF*	*F Value*	*Pr > F*
*trt*storm*	1	2	22.6	0.96	0.3973
*trt*storm*	2	2	22.6	22.49	<.0001
*trt*storm*	3	2	22.6	0.61	0.5529
*trt*storm*	4	2	22.6	0.93	0.4076


Studentized Residuals for SedLoss
Residual
Predicted Mean
Percent
Residual
Residual
Quantile
Residual Statistics
Observations 60
Minimum -2.127
Mean -3E-17
Maximum 3.3337
Std Dev 1.0084
Fit Statistics
Objective 271.9
AIC 279.9
AICC 280.83
BIC 278.34


Conditional Studentized Residuals for SedLoss
Residual
Predicted
Percent
Residual
Residual
Quantile
Residual Statistics
Observations 60
Minimum -2.127
Mean 11E-18
Maximum 3.5842
Std Dev 1.0735
Fit Statistics
Objective 271.9
AIC 279.9
AICC 280.83
BIC 278.34

Storm 1

Obs	Effect	trt	_trt	_storm	Estimate	StdErr	DF	tValue	Probt
4	trt*storm	Aerated	Control	1	5.8605	4.2500	22.1	1.38	0.1817
11	trt*storm	Aerated	Tilled	1	5.3505	3.9132	16.5	1.37	0.1898
15	trt*storm	Control	Tilled	1	-0.5100	1.8059	18.7	-0.28	0.7807

Storm 2

Obs	Effect	trt	_trt	_storm	Estimate	StdErr	DF	tValue	Probt
25	trt*storm	Aerated	Control	2	23.3220	4.2500	22.1	5.49	<.0001
31	trt*storm	Aerated	Tilled	2	26.1280	3.9132	16.5	6.68	<.0001
35	trt*storm	Control	Tilled	2	2.8060	1.8059	18.7	1.55	0.1370

Storm 3

Obs	Effect	trt	_trt	_storm	Estimate	StdErr	DF	tValue	Probt
43	trt*storm	Aerated	Control	3	1.3600	4.2500	22.1	0.32	0.7520
48	trt*storm	Aerated	Tilled	3	2.9157	3.9132	16.5	0.75	0.4667
52	trt*storm	Control	Tilled	3	1.5557	1.8059	18.7	0.86	0.3999

Storm 4

Obs	Effect	trt	_trt	_storm	Estimate	StdErr	DF	tValue	Probt
58	trt*storm	Aerated	Control	4	-0.3200	4.2500	22.1	-0.08	0.9407
62	trt*storm	Aerated	Tilled	4	2.0340	3.9132	16.5	0.52	0.6101
66	trt*storm	Control	Tilled	4	2.3540	1.8059	18.7	1.30	0.2082

Stormwater Runoff

Model Information	
Data Set	WORK.A
Dependent Variable	runoff
Covariance Structure	Variance Components
Subject Effect	rep*trt
Group Effect	trt
Estimation Method	REML
Residual Variance Method	None
Fixed Effects SE Method	Kenward-Roger
Degrees of Freedom Method	Kenward-Roger

Class Level Information		
Class	*Levels*	*Values*
rep	5	1 2 3 4 5
trt	3	Aerated Control Tilled
storm	4	1 2 3 4

Dimensions	
Covariance Parameters	5
Columns in X	20
Columns in Z	20
Subjects	1
Max Obs Per Subject	60

Number of Observations	
Number of Observations Read	60
Number of Observations Used	60
Number of Observations Not Used	0

Iteration History			
Iteration	*Evaluations*	*-2 Res Log Like*	*Criterion*
0	1	392.03257027	
1	2	327.61108121	0.00467832
2	2	327.31122024	0.00029815
3	1	327.27883699	0.00000497
4	1	327.27823654	0.00000000

Convergence criteria met.

Covariance Parameter Estimates			
Cov Parm	*Subject*	*Group*	*Estimate*
rep			0.4931
*rep*trt*			0
Residual	rep*trt	trt Aerated	26.8118
Residual	rep*trt	trt Control	381.14
Residual	rep*trt	trt Tilled	4.0116

Fit Statistics	
-2 Res Log Likelihood	327.3
AIC (smaller is better)	335.3
AICC (smaller is better)	336.2
BIC (smaller is better)	333.7

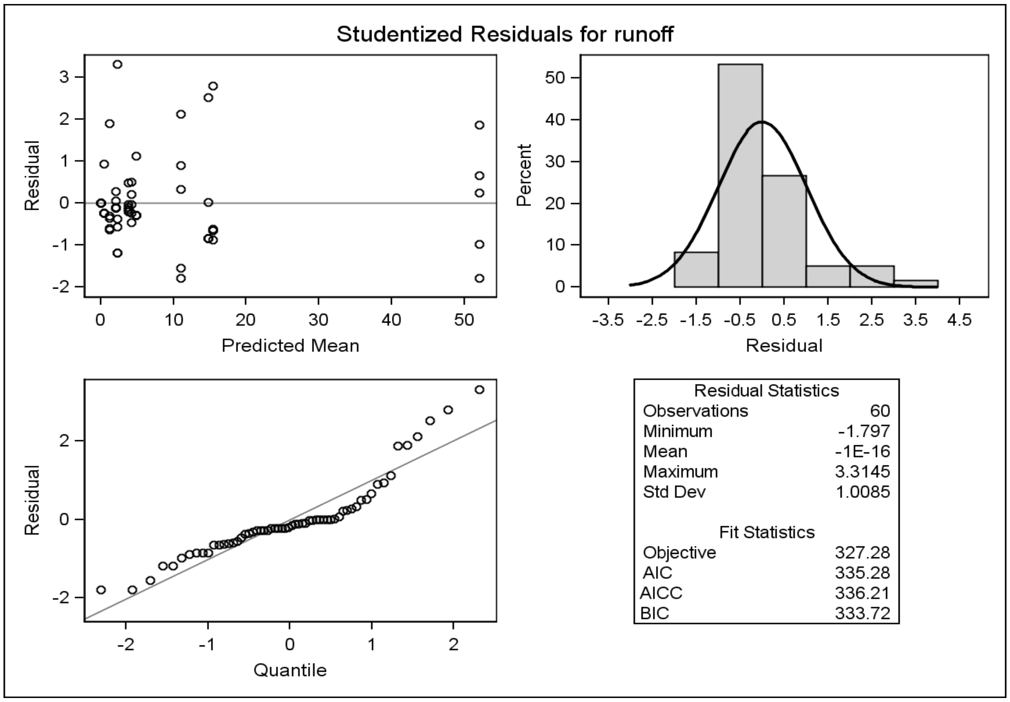
Type 3 Tests of Fixed Effects				
Effect	*Num DF*	*Den DF*	*F Value*	*Pr > F*
storm	3	18.6	9.26	0.0006
trt	2	23.3	90.07	<.0001
*trt*storm*	6	26.4	43.78	<.0001

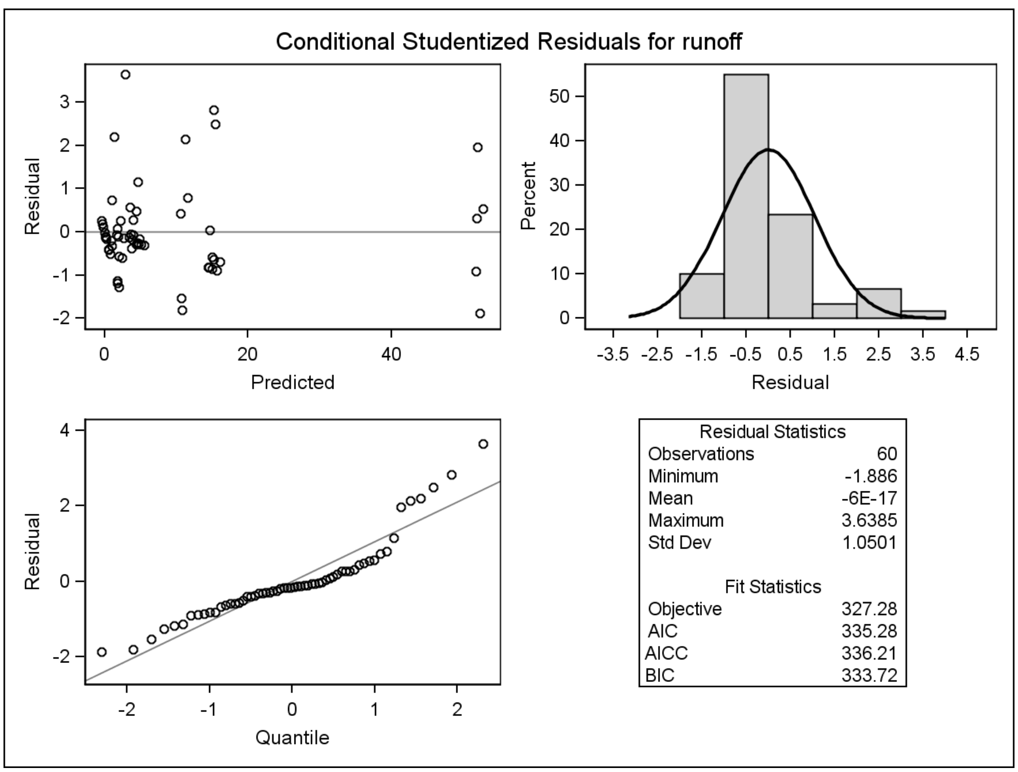
Least Squares Means

Effect	*trt*	*storm*	*Estimate*	*Standard Error*	*DF*	*t Value*	*Pr > |t|*
*trt*storm*	Aerated	1	3.8420	2.3369	16.5	1.64	0.1191
*trt*storm*	Aerated	2	52.0600	2.3369	16.5	22.28	<.0001
*trt*storm*	Aerated	3	4.2180	2.3369	16.5	1.80	0.0894
*trt*storm*	Aerated	4	11.0000	2.3369	16.5	4.71	0.0002
*trt*storm*	Control	1	2.0526	8.7365	16	0.23	0.8172
*trt*storm*	Control	2	14.8040	8.7365	16	1.69	0.1095
*trt*storm*	Control	3	4.9140	8.7365	16	0.56	0.5816
*trt*storm*	Control	4	15.4460	8.7365	16	1.77	0.0961
*trt*storm*	Tilled	1	1.1900	0.9492	15.8	1.25	0.2282
*trt*storm*	Tilled	2	-444E-18	0.9492	15.8	-0.00	1.0000
*trt*storm*	Tilled	3	0.4400	0.9492	15.8	0.46	0.6493
*trt*storm*	Tilled	4	2.2580	0.9492	15.8	2.38	0.0304

Tests of Effect Slices

Effect	*storm*	*Num DF*	*Den DF*	*F Value*	*Pr > F*
*trt*storm*	1	2	23.3	0.56	0.5807
*trt*storm*	2	2	23.3	214.15	<.0001
*trt*storm*	3	2	23.3	1.23	0.3118
*trt*storm*	4	2	23.3	6.94	0.0043


Studentized Residuals for runoff
Residual
Predicted Mean
Percent
Residual
Residual
Quantile
Residual Statistics
Observations 60
Minimum -1.797
Mean -1E-16
Maximum 3.3145
Std Dev 1.0085
Fit Statistics
Objective 327.28
AIC 335.28
AICC 336.21
BIC 333.72


Conditional Studentized Residuals for runoff
Residual
Predicted
Percent
Residual
Residual
Quantile
Residual Statistics
Observations 60
Minimum -1.886
Mean -6E-17
Maximum 3.6385
Std Dev 1.0501
Fit Statistics
Objective 327.28
AIC 335.28
AICC 336.21
BIC 333.72

Storm 1

Obs	Effect	trt	_trt	_storm	Estimate	StdErr	DF	tValue	Probt
4	trt*storm	Aerated	Control	1	1.7894	9.0328	18.2	0.20	0.8452
11	trt*storm	Aerated	Tilled	1	2.6520	2.4829	20.2	1.07	0.2981
15	trt*storm	Control	Tilled	1	0.8626	8.7767	16.3	0.10	0.9229

Storm 2

Obs	Effect	trt	_trt	_storm	Estimate	StdErr	DF	tValue	Probt
25	trt*storm	Aerated	Control	2	37.2560	9.0328	18.2	4.12	0.0006
31	trt*storm	Aerated	Tilled	2	52.0600	2.4829	20.2	20.97	<.0001
35	trt*storm	Control	Tilled	2	14.8040	8.7767	16.3	1.69	0.1107

Storm 3

Obs	Effect	trt	_trt	_storm	Estimate	StdErr	DF	tValue	Probt
43	trt*storm	Aerated	Control	3	-0.6960	9.0328	18.2	-0.08	0.9394
48	trt*storm	Aerated	Tilled	3	3.7780	2.4829	20.2	1.52	0.1436
52	trt*storm	Control	Tilled	3	4.4740	8.7767	16.3	0.51	0.6170

Storm 4

Obs	Effect	trt	_trt	_storm	Estimate	StdErr	DF	tValue	Probt
58	trt*storm	Aerated	Control	4	-4.4460	9.0328	18.2	-0.49	0.6285
62	trt*storm	Aerated	Tilled	4	8.7420	2.4829	20.2	3.52	0.0021
66	trt*storm	Control	Tilled	4	13.1880	8.7767	16.3	1.50	0.1521