Quantifying the Effectiveness of Soil Remediation Techniques in Compact Urban Soils

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Finally, I wish to express a special thank you to all of the Saint Anthony Falls Laboratory staff. I am fortunate for the broad experience I gained working with very talented people.

Dedication

I would like to dedicate this thesis to my father, John Olson, and to my grandparents Tod and Jacquelyn Olson, for their continuous encouragement and wisdom. I would not have made it this far in my educational career without their love and support.

Finally, this dedication is also for a good friend and my "proxy grandmother," Mrs. Sally Tang. I've never been shown such kindness from anyone before and I am deeply saddened by your passing.

Abstract

Soils in urban environments typically have lower stormwater infiltration rates than the soils they replace due to reduced topsoil depth and increased subsoil compaction from land development. Loss of infiltration leads to increased stormwater runoff and associated downstream problems: flooding, pollutant transport, and warming stream temperatures.

A field experiment was conducted to determine the effectiveness of remediation techniques to alleviate soil compaction and increase infiltration. Deep tillage and compost addition are two techniques commonly used in agricultural practices to reduce the level soil compaction. These techniques were implemented on three sites in the metropolitan area. Each site was divided into three plots: tilled, tilled with compost addition, and a control plot for comparison. To determine the effectiveness of each remediation technique, before and after measurements of saturated hydraulic conductivity (Ksat), soil bulk density, and soil strength were used to assess the level of compaction.

Deep tillage was effective at reducing the level of soil strength. Soil strength was approximately half that of the control plot in the first six inches of soil. However, tilling did not significantly improve the bulk density of the soil. At two of the sites, tilling was ineffective at improving that infiltration capacity of the soil. Tilling may have damaged natural pathways in the soils, thus reducing the permeability. Tilling was effective at remediating the soil at one site, which was not as well-established at the previous two sites. The geometric mean of Ksat was 2.1 to 2.3 times that of the control plot

Compost addition was the most effective soil remediation technique. Similar reductions in soil strength were found as the till plot. Soil bulk densities on the compost plots were 18-37% lower than the control plot. The infiltration capacity of the soil was improved. The geometric mean of Ksat on the compost plots was 2.7 to 5.7 times that of the control plot.

The results of these findings will be useful in revising stormwater best management practices to include guidelines on soil compaction prevention and remediation of compacted sites.

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Chapter One

Project Overview

This thesis is based on a collaborative project by the Three Rivers Park District (TRPD) and the University of Minnesota to quantify the effectiveness of soil remediation to improve stormwater infiltration. Funding was provided by the Minnesota Pollution Control Agency (MPCA) under the title, "Quantifying Stormwater Infiltration Rates on Developed Soils Amended with Tillage and Compost." Additional funding was provided by the University of Minnesota's Center for Urban and Regional Affairs (CURA) under the project title, "Tilling and Composting Compacted Soils to Decrease Urban Runoff". John Barton, Director of Natural Resources at TRPD was the original grant project manager. Randy Lehr, Director of Water Resources, took over as project manager during the first summer of the project. The principal investigators (PIs) from the University of Minnesota were Dr. John S. Gulliver, professor from the Department of Civil Engineering, and Dr. John L. Nieber, professor from the Department of Bioproducts and Biosystems Engineering.

The Three Rivers Park District (TRPD) provided the project with two project sites. They were located within Clifton E. French Regional Park (Plymouth, MN) and Lake Minnetonka Regional Park (Minnetrista, MN). A third site was arranged by the TRPD and the City of Maple Grove. This site was located within Maple Lakes Park, in

Maple Grove, MN. TRPD was responsible for providing the soil remediation work at all sites. The compost used in this project was provided by Plaisted, Inc.

The investigative work on the effectiveness of the soil remediation techniques was performed by the University of Minnesota. Previously, the University of Minnesota had completed work on an assessment technique used to quantify the infiltration capacity of raingardens (Asleson et al. 2007). The product of this research was the Modified Philip-Dunne Permeameter (MPD), an infiltration measurement device that uses a falling head technique to measure the saturated hydraulic conductivity of a soil. The MPD is easily constructed, uses a minimal amount of water, and requires less time than standard devices like the double ring infiltrometer. The advantages of this device allow one to make several measurements of saturated hydraulic conductivity, which is necessary in soils that have large variability. The MPD was used before and after the soil remediation techniques were applied assess the effectiveness of each technique to improve infiltration capacity.

Chapter Two

Introduction

2.1 Stormwater Challenges

The increase in urbanization has significantly increased the amount of stormwater runoff in watersheds, creating challenging problems for hydrologists. Development conditions rarely replicate pre-development hydrology (Figure 2.1.1). Impervious surfaces, such as roads, roofs, and compacted soils reduce infiltration of stormwater. This reduction leads to increased runoff volume and increased peak flows during and after a storm event, which can cause flooding and downstream erosion.

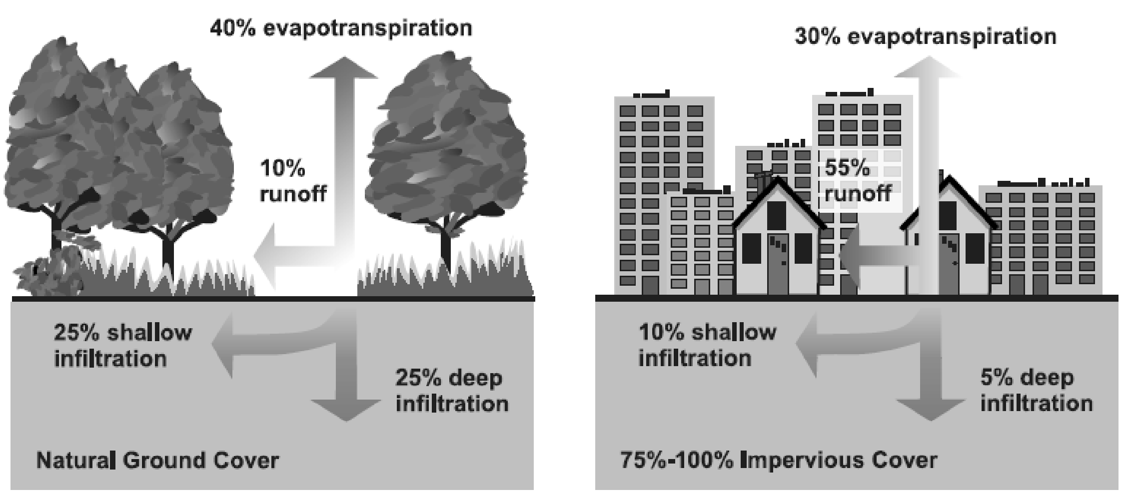

Figure 2.1.1 The water cycle for pre-development conditions (left) and post-development (right) (EPA, 2003).

Excess runoff also amplifies non-point source pollution. The runoff picks up debris and sediments, depositing them in lakes and rivers. Other concerns are heavy metals, chemicals, excess nutrients, and salt being transported during storm events, increasing contamination to receiving waters. Stormwater mitigation is paramount to meet current regulations and the future needs of an ever expanding populous.

Several stormwater management practices are used to mitigate the effects of additional runoff caused by urbanization. A popular solution has been the use of detention ponds. While detention ponds help reduce the peak outflow from a storm, the volume of water being transported is not reduced (Brander et al., 2004) and pollution load is still substantial. Current trends in stormwater management are thus focused on finding ways to allow rainwater to infiltrate into the ground to reduce peak flow. Infiltration provides the benefit of reducing the transport of pollution through filtration of particles and adsorption of chemicals to the soil. It also reduces the need for stormwater sewers and storage because, in addition to lowering the peak outflow the volume of water being transported is also decreased.

There are several infiltration practices growing in popularity to manage stormwater: rain gardens, pervious pavements, roof gardens, soil amendments, etc. This thesis will review the use of soil amendments in urban soils to remediate soil compaction caused by development as a supplement current to stormwater management practices.

2.2 Effects of Soil Compaction

Soil compaction in developed areas is a consequence of commercial and residential site development. Tremendous amounts of force are used to shape and stabilize a site for development. Compression, displacement, and mixing are examples of processes that can lead to the over-compaction of a soil (Batey and McKenzie, 2006).

These processes are often caused by the traffic of heavy equipment used to develop sites (Gregory et al., 2006). Developments sometimes have the topsoil in the area removed prior to construction, which leaves the subsoil susceptible to compaction (Hamilton and Waddington, 1999). A thin layer of topsoil is then placed on top of the subsoil, likely without mechanical loosening of the subsoil. The effects of compaction may last for decades before the soil is able to recover (Pitt et al., 2002). Researchers have shown that clayey soils, in particular, are susceptible to compaction (Pitt et al., 2002) and have a lower stress relaxation rate after being compacted (Sanchez-Giron et al., 2001).

Compaction reduces the amount of pore space by compressing the soil matrix (Craul, 1994), and macropore pore space is also significantly reduced with soil compaction (Shestak and Busse, 2005). Figure 2.2.1 shows the decrease in total porosity and pore sizes with increased levels of compaction.

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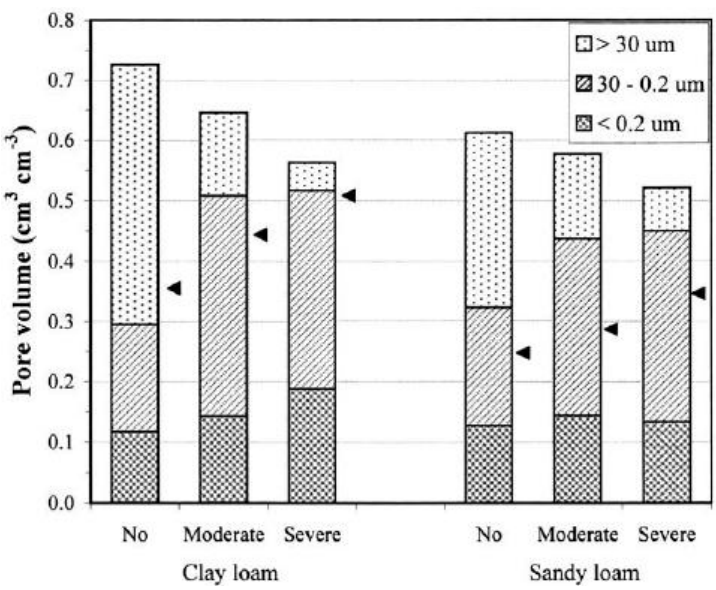

Figure 2.2.1 The effect of compaction on pore size in two types of soil (Shestak and Busse, 2005). Arrows show the volumetric moisture content at the time of experiment. The level of compaction was a 15% reduction in soil volume for the moderate level, and 30% for severe compaction.

Other researchers found similar decreases in total pore volume and re-distribution of pore sizes from larger to smaller after compaction from wheeled traffic (Schafer-Landefeld et al., 2004). Their results are shown in Figure 2.2.2, which looks at larger pore sizes than Shestak and Busse (2005). Figure 2.2.2 shows the pore volume to soil volume ratio at three depth ranges in a silt loam soil. The "top soil" was considered to be 15 to 20 cm depth range, plough pan was in the 25 to 30 cm depth range, and the subsoil was in the 38 to 43 cm depth range.

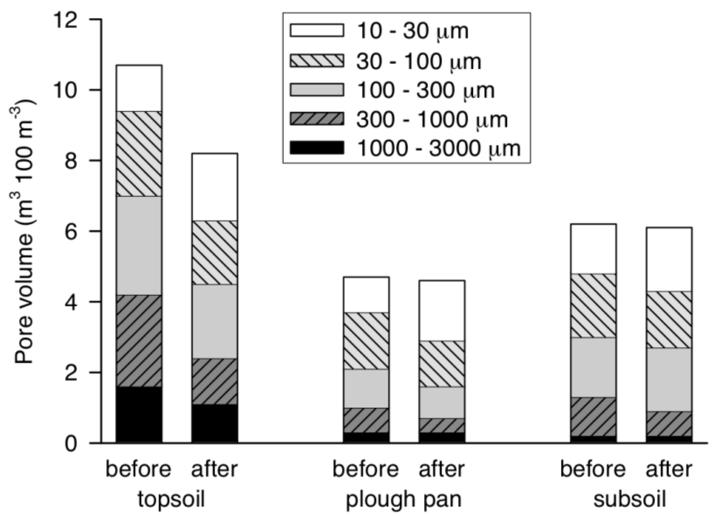

Figure 2.2.2 The effects of wheeled traffic in different layers of soil (Schafer-Landefeld et al., 2004).

Loss of larger pore sizes and the number of pores cause decreases in the permeability of air and water, as well as lowering water-holding capacity, and can reduce root penetration into the soil (Craul, 1994 and Gregory et al., 2006). The pores between soil particles are reduced in size, which creates resistance to air and water passage. As illustrated in Figure 2.2.3, roots have difficulty penetrating compacted soil because the pores have to be at least as big as the root tips (Craul, 1994). Roots obtain moisture from the soil and lateral or deeper penetration may be needed to obtain that moisture. The reduction of tree and plant growth will also lead to increased runoff because of increased antecedent moisture content caused by a decrease in transpiration (Bartens et al., 2008).

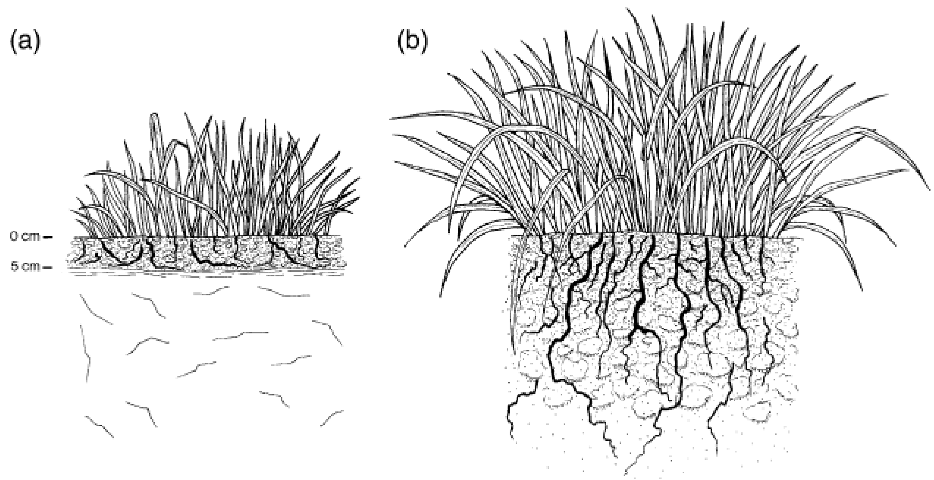

Figure 2.2.3 The affects of compaction on grass growth (a) shallow compaction (b) no compaction. Reproduced by Batey and McKenzie (2006) from Soil Husbandry.

2.3 Assessment Techniques

To assess the level of compaction it is important to choose soil properties that can be easily measured in the field. Since there is no universal method developed to assess the compaction level and its effects, a combination of indirect and direct measurements can/should be used (Batey and McKenzie, 2006). Three commonly used measurements are: saturated hydraulic conductivity, soil bulk density, and soil strength. Saturated hydraulic conductivity (Ksat) is a permeability coefficient used in Darcy's Law, which quantifies the flux of water into a soil (See Equation 2.3.1)

$$q = -K_{sat} \frac{\partial h}{\partial z} \qquad (2.3.1)$$

where,

q is the flux rate of water into the soil [Length/Time]

$\frac{\partial h}{\partial z}$ is the hydraulic gradient

A reduction in Ksat may be an indication that there is a loss of porosity, which can result from soil compaction. Soil bulk density is a more direct measure of soil compaction. High values of bulk density indicate that there is more mass of soil solids confined in a unit volume of soil. Finally, soil strength is a measure of the resistance of an object to penetrate the soil matrix. More compact soils generally have a higher soil strength.

2.4 Previous Research

Several researchers have used combinations of two or more of these assessment techniques to measure the level of compaction in soil compaction studies: Gregory et al. (2006), Hamilton and Waddington (1999), Ocean County Soil Conservation District Report (2001), Ozgoz et al. (2006), and Pitt et al. (2002). Listed in Table 2.4.1 are results from these field studies looking at the effects of compaction at disturbed and undisturbed locations. Table 2.4.1 is provided on the next few pages.

Table 2.4.1 The properties of disturbed and undisturbed soils from five field studies.

Study	Description	Area Tested:	Soil Disturbance	Soil Type	Assessment Measurements: Infiltration Rate* [cm/hr]	Bulk Density [g/cm^3]	Soil Strength [MPa]
Gregory et al. (2006)	Study on urban soil compaction in North Central Florida	2 Naturally Wooded Lots, 1 Planted Lot	Undisturbed	Sandy	73.3	1.34	Max: 1.07 to 1.91
			Construction Vehicle Traffic	Sandy	17.8	1.49	Max: 1.97 to 3.74
		In Wheel Ruts	Dump Truck	Sandy	2.3	1.68	n/a
			Back Hoe	Sandy	5.9	1.61	n/a
			Pickup	Sandy	6.8	1.61	n/a

Table 2.4.1 Continued.

Hamilton and Waddington (1999)	Study on lawn infiltration rates in Pennsylvania	Various Residential Lawns	Undisturbed	Clay Loam	10	1.35	n/a
			Filled	Loam, Clay Loam	4.9 to 5.1	1.49 to 1.59	n/a
			Excavation	Sandy Loam, Loam, Silt, & Clay	0.4 to 9.8	1.02 to 1.59	n/a
Ocean County Soil Conservation District (2001)	Study on soil infiltration rates on modified and compacted sites	Woods	Undisturbed	Mostly Sandy Loam	38.1	1.42	n/a
		Single House	Somewhat Disturbed (not specified)	Loamy Sand	18.03	1.67	n/a
		Subdivision Lawn 1	Disturbed (not specified)	Loamy Sand	0.36	1.79	n/a
		Subdivision Lawn 2	Disturbed (not specified)	Loamy Sand	0.08	2.03	n/a

Table 2.4.1 Continued.

		Athletic Field	Disturbed (not specified)	Loamy Sand	0.03	1.95	n/a
Ozgoz et al. (2006)	Study on the effects of tractor wheel traffic on an agricultural soil	10-15 cm Soil Depth Location 1	No Traffic	Sandy Clay Loam	0.52	1.58	1.39
			Tractor (Five Passes)	Sandy Clay Loam	1.05	1.65	2.48
		10-15 cm Soil Depth Location 2	No Traffic	Clay Loam	0.71	1.53	0.62
			Tractor (Five Passes)	Clay Loam	0.01	1.57	1.39
		10-15 cm Soil Depth Location 3	No Traffic	Clay Loam	n/a	1.55	0.91
			Tractor (Five Passes)	Clay Loam	0.12	1.48	1.64

Table 2.4.1 Continued.

Pitt et al. (2002)	Study on compacted urban soils in Alabama	Sandy Soils	Not Compact (by soil strength definition)	Sandy	33.02	n/a	< 300 psi (2.1 MPa) within top 3"
			Compact (by soil strength definition)	Sandy	3.56	n/a	> 300 psi (2.1 MPa) within top 3"
		Clayey Soils	Not Compact (by soil strength definition)	Clayey	24.90	n/a	< 300 psi (2.1 MPa) within top 3"
			Compact (by soil strength definition)	Clayey	0.51	n/a	> 300 psi (2.1 MPa) within top 3"

*Infiltration rate is not the same thing as the Ksat. Ksat can be computed from the infiltration rate, but one need to take into account the hydraulic gradient. "Infiltration rate" from Ocean County Soil Conservation District, 2001 and Ozgoz et al., 2006 are actually measurements of Ksat.

The infiltration rates between studies differed from each other but the relative rates within each study will be helpful. The maximum infiltration rate was 73.3 cm/hr and was found in an undisturbed sandy soil (Gregory et al., 2006). The lowest infiltration rate was 0.01 cm/hr in a clay loam soil after it had been compacted by a tractor (Ozgoz et al., 2006). Ocean County Soil Conservation District (2001) had up to three orders of magnitude difference in Ksat between the most disturbed site and the least disturbed site they tested. Other studies found an average decrease of one order of magnitude in infiltration rate between undisturbed and disturbed sites. The lowest infiltration rates were found in sandy loam and clay loam soils. Field tests from Pitt et al. (2002) showed that compact sandy soils had infiltration rates that were 89% lower than non-compact sandy soils. Compact clayey soils were 98% lower than non-compact clayey soils (Pitt et al., 2002). Ozgoz et al. (2006) had a similar finding in a clay loam soil that decreased in infiltration by 98% after being compacted.

Bulk densities were also variable between the studies. Ocean County Soil Conservation District (2001) found the highest bulk densities of all the studies (2.03 g/cm^3), which they believed would restrict root growth. Gregory et al. (2006) measured the bulk density in the wheel ruts of different construction vehicles and found bulk densities that were up to 20% greater than the average value for three undisturbed sites used in the study. However, Ozgoz et al. (2006) also studied the affects of wheel traffic on soil compaction and found minimal differences in bulk density between disturbed and undisturbed areas.

Soil strength was measured in three of the five studies. Gregory et al. (2006) found the highest levels of soil strength (up to 3.74 MPa). Results from Ozgoz et al. (2006) showed that the soil strength increased ~1.8 to 2.2 times from five passes of a tractor in their soil. Pitt et al. (2002) used soil strength as a definition to distinguish between compact and non-compact soil. Their study stated that a soil is considered to be compact if the soil strength in the top three inches of soil exceeds 300 psi (~2.1 MPa). By this definition, the soil strengths found by Gregory et al. (2006) and Ozgoz et al. (2006) would not be considered compact.

There are a lot of variables to consider when assessing a site for compaction. The soils between studies listed in Table 2.4.1 are likely to be very different and it would be hard to correlate their results to each other. The researchers also used different methods to measure and/or calculate the different soil properties. Table 2.4.1 showed that there was not always correlation between the soil properties measured, either. It would be difficult to determine when a site is compact if the results of other field studies were used. Pitt et al. (2002) recommends that researchers who are interested in using soil remediation to alleviate soil compaction should perform localized testing to better understand the effects of compaction and the possible benefits from remediation.

Chapter Three

Soil Remediation Techniques

The use of soil amendments may be a way to reduce the problems associated with urban soils and compaction. Using amendments is often more feasible then soil replacement, which is expensive and limited to local materials (Craul, 1994). Two remediation techniques, commonly used in agricultural practices to yield better crops, are tillage and compost addition. Tilling and compost addition can alleviate soil compaction, enhance infiltration rates, establish better plant growth, and reduce stormwater runoff. A review of these techniques is provided in this chapter to examine their suitability to reduce soil compaction in an urban setting.

3.1 Tillage

Tillage is a common practice used in agricultural settings to loosen and mix the topsoil. A tiller has tines, which are pulled through the soil by a tractor. An upward motion of the soil is created as the tines move through the soil, which causes the soil to dilate and create tensions cracks. (Spoor, 2006). Figure 3.1.1 illustrates the process of tilling.

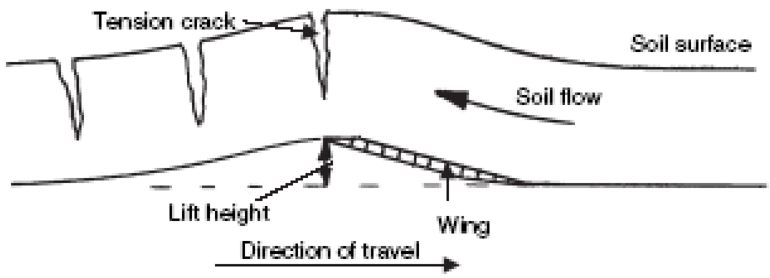

Figure 3.1.1 A winged tine of a tiller uplifting a soil to produce tension cracks (Spoor, 2006).

To alleviate compaction, the tines can be pulled through the subsoil layer, in a process known as sub-soiling or deep tillage. The goal of deep tillage is to break up 'pans' or hard subsurface layers by creating vertical fissures (Spoor, 2006). Vertical fissures are useful in providing drainage as well as providing better conditions for root development (Spoor, 2006).

Several studies have shown that deep tillage improves infiltration and plant growth. In three silt loam soils in Illinois, tilled soils had larger total pore volume and a greater number of large macropores (> 150 μm) and small macropores (15-150 μm) than non-tilled soils (Yoo et al., 2006). These tilled soils would be expected to have higher infiltration rates than their non-tilled counterparts. Chaplin et al. (2008) found low cost benefits in alleviating the effects of soil compaction in right-of-way areas adjacent to roads. They found that just a single pass of a tilling operation decreased the drainage time by one third over the control area in a sandy loam soil (Chaplin et al., 2008). In an infiltration study of an agricultural field, Meek et al. (1992) compared the effects of traffic and tillage on infiltration rates (See Figure 3.1.2). Tilled soils with traffic (farm equipment) outperformed trafficked soils with no tillage. Chen et al. (2005) found that sub-soiling improved crop emergence, plant population density, and crop yield.

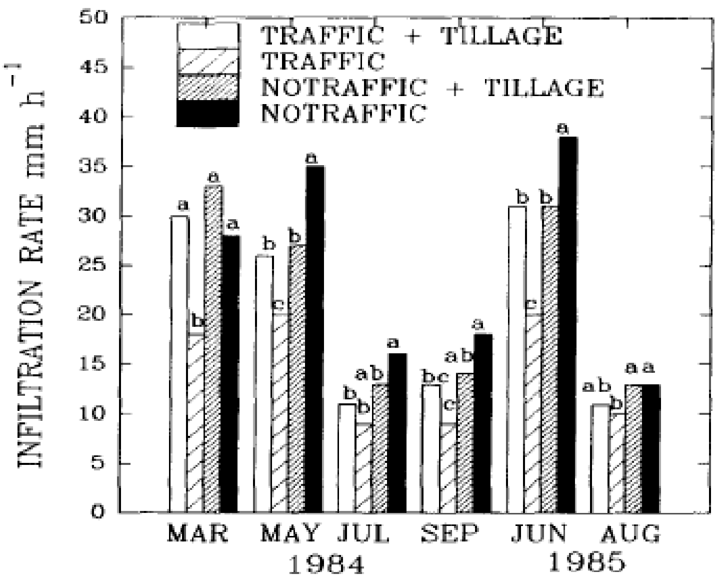

Figure 3.1.2 The changes in infiltration during two growing seasons (Meek et al., 1992). Values within a date designated with the same letter are not statistically different.

Tilling practice may also influence the soil properties negatively. Figure 3.1.2 showed that soils with little to no traffic that were tilled had lowered infiltration rates than non-trafficked soils without tillage (Meek et al., 1992). A few researchers have explained that tillage may sometimes disturb the natural soil structure (e.g. earthworm or ant tunnels), which can reduce infiltration capacity (Meek et al., 1992; Schafer-Landefeld et al., 2004; and Spoor, 2006). Others found that there was no significant reduction in soil strength from tilling operations (Chaplin et al., 2008; Chen et al., 2005). The effects of tilling may degrade from re-compaction and require repeat tillage treatments (Henderson et al., 1988; Schafer-Landefeld et al., 2004). The use of deep tillage may be difficult in an urban setting. Utility congestion (Chaplin et al., 2008), established trees, and other obstacles would limit the remediable area and make tilling operations more difficult.

3.2 Compost Addition

Compost addition involves comingling soil with a highly organic component. Compost comes in a variety of forms. It can be made from municipal solid waste, manure, biosolids, coal ash, food, and leaf composts (Cogger, 2005). Compost works by aggregating soil particles (sand, silt, and clay) into larger particles (Cogger, 2005). Organic mineral complexes in the compost create water-soluble cement that binds the soil particles together (Craul, 1994). Aggregation of soil particles creates additional porosity, which reduces the bulk density of the soil (Cogger, 2005). Compost can also reduce the bulk density of a soil by dilution of the mineral matter in the soil (Cogger, 2005). When the porosity of the soil increases and the particle surface area increases, water holding capacity is also increased (Cogger, 2005). Increases in macropore continuity have been found as well (Harrison et al., 1998). Compost therefore should increase the water holding capacity and improve the infiltration rate.

Studies have cited numerous beneficial abilities of compost: increased water drainage, increased water holding capacity, increased plant production, increased root penetrability, reduction of soil diseases, reduction of heavy metals, and the ability to treat many chemical pollutants (EPA, 1997; Harrison et al., 1998; WDOE Stormwater Management Manual, 2007). Harrison et al. (1998) field tested a compost-amended soil (2:1 soil to compost mix) and compared it to a control soil. They found several benefits: the water-holding capacity of the soil was increased by 46%, bulk density was reduced from 1.7 to 1.1 g/ cm^3, porosity increased from 41% to 48%, and volumetric moisture capacity was increased to 50% from 46% (Harrison et al., 1998). EPA (1997) cited two military golf course studies that used compost to reduce soil compaction and improve turf areas. One golf course at Fort George Meade, Maryland used compost mixed into 3-5" of soil and estimated that they will save ~ $50,000/year in maintenance costs (EPA, 1997). The U.S. Air Force Golf Course in Colorado Springs, Colorado also found reduced costs from compost-amended turf areas, which "…required up to 30% less water, fertilizer, and pesticides than turf treated conventionally" (EPA, 1997). The effects of compost addition do not degrade as fast as just tilling (Pitt et al., 2002). The benefits of compost may be long term. The longevity isn't certain, but Cogger (2005) reviewed several compost studies that suggest that compost treatments are still viable over five years after initial treatment.

Although the effects of compost addition are numerous and expected to outlast tillage alone, some consequences can result from their use. Compost has a lot of nutrients incorporated into it, and rainfall runoff may cause nutrient leaching from compost-amended areas (Harrison et al., 1998; Pitt et al., 2002). Runoff testing performed by Harrison et al. (1998) showed that there were higher concentrations of phosphorus and nitrogen species in the compost-amended soil over the control soil. Pitt et al. (2002) believes that using less compost could result in similar benefits with the reduced problem of nutrient leaching. High salt concentrations in some compost materials could be of concern for low salt tolerant plant species (Cogger, 2005). An excessive amount of compost placed over compacted soils may increase waterlogging, which would create anaerobic soil conditions (Cogger, 2005).

A combination of tilling and compost addition may provide the greatest benefit to improving urban soils. Tilling may be necessary to help incorporate compost into very compact soils. If a soil is heavily trafficked, than compost may help prevent the re-compaction of the soils better than soils remediated with tillage alone. The cost of these solutions is dependent on available resources and their location (Craul, 1994). Brander et al. (2004) suggests deep tilling with compost should be performed after construction to improve infiltration in turf areas. Sites in the process of being developed could see a lower cost of tilling with compost due to a larger scale operation than remediating developed sites. This thesis will quantify the effectiveness of tilling and tilling with compost addition to alleviate soil compaction and improve infiltration in already developed locations.

Chapter Four

Site Selection

4.1. Selection Criteria

The Three Rivers Park District (TRPD) selected three study sites around the Minneapolis Metropolitan area to test different soil remediation techniques. They were required to be turf areas, easily accessed by remediation equipment, differ in soil type, and have a nearby water supply. An examination of each site's history was taken into account to estimate the level of compaction. Soil types from the United States Department of Agriculture (USDA) Web Soil Survey were also used in assessing each site.

The specific areas to be examined in the sites were then chosen based upon a visual inspection. Visual clues used were: relative hardness of the ground, poor turf establishment, poor tree growth or exposed roots, and eroded or bare soil areas. Poor turf establishment suggests difficulty for the grass roots to penetrate into the soil, reducing their ability to reach more moist soil. Similarly, poor tree growth indicated the inability for roots to penetrate into the subsoil, causing some roots to become exposed.

4.2 Sites

The sites selected for testing the impact of soil remediation on infiltration include, French Regional Park (City of Plymouth), Lake Minnetonka Regional Park (City of Minnetrista), and Maple Lakes Park (City of Maple Grove).

4.2.1 Lake Minnetonka Regional Park

Lake Minnetonka Regional Park is one of the Three Rivers Park District's public properties. It was originally privately owned and then later deeded to the park district. When the property was deeded, an extensive tree installation program went under way as well as the construction of a large swimming pond. Interviews with different park employees suggest the use of large and heavy equipment to construct the swimming pond as well as establishing the new trees. The site had a difficult time establishing the trees, presumably due to the high level of soil compaction from the construction equipment. This is apparent in one area of the park where the tree sizes are relatively small. Other areas were tilled before the tree installation. The trees there are well established and much larger. The TRPD has used remediation techniques in the past outside of the swim pond area to encourage tree growth. This included tilling and incorporating additional soil.

Historically, the soils in this area are designated by the USDA Web Soil Survey as Lester Loam and Hammel soil types. The parent material is glacial till. The texture is a loam from 0" to up to 12" and a clay loam from 12" to 36" or greater. The soil has an expected saturated hydraulic conductivity of 0.51 to 5.10 cm/hr (or 0.20 to 2.00 in/hr).

The selected area in the site for this experiment is a half-acre picnic area adjacent to the swim pond. Park employees maintain the area annually. Visual inspection revealed trampled regions from visitors that traverse the area as they move from the parking lot to the swim pond facilities. The trees in this area are small and some have struggled to survive. The turf had dying or bare areas, but was mostly healthy.

4.2.2 French Regional Park

French Regional Park is another property owned by the Three Rivers Park District on the north side of Medicine Lake. The area was originally residential property with a highway intersecting it. Part of the property was converted to a large beach and picnic area. The native soils in the picnic area were mixed and/or filled with peatland soils from an adjacent lagoon area. This indicated a highly disturbed area, which could result in significant soil compaction. Similarly to Lake Minnetonka Regional Park, trees in this area have had difficulty establishing themselves in the turf areas. Some trees were removed just prior to the start of this study.

USDA Web Soil Survey classifies the soil in this area as Muskego, Blue Earth, and Houghton soils, as well Glencoe Loam. Anecdotal evidence suggests the research area was mostly composed of the Muskego, Blue Earth, and Houghton soils, but was filled from soil borrowed just outside of this area, which is mostly Glencoe Loam. Muskego, Blue Earth, and Houghton soils are composed of muck, or highly organic marshland soil. These soils have an expected saturated hydraulic conductivity of 0.15 to 0.51 cm/hr (or 0.06 to 0.20 in/hr). The Glencoe Loam is loam with clay loam layer below 13". This soil has an expected saturated hydraulic conductivity of 0.51 to 5.10 cm/hr (or 0.20 to 2.00 in/hr).

The selected area in the site for this study is a half-acre picnic area adjacent to the beach. Park employees maintain this area annually. Visual inspection revealed a few trees with shallow or exposed roots. Some trees were marked for removal, but this may not have been due solely to soil compaction. The turf in this area was very dry and the grass in many areas was dying. Bare soil was evident on the edges of the turf area.

4.2.3 Maple Lakes Park

The basis for selecting Maple Lakes Park was its unique construction history. This park is in a newly developed area next to a stormwater pond as well as a groundwater fed pond. Maple Grove has transformed from a large sand and gravel extraction area into a large suburban area with many large residential developments. Most of the residential areas are less than ten years old and new developments are currently being constructed less than half of a mile from the park. The large amount of sand and gravel extraction and grading operations are believed to have caused a high level of soil compaction. It is not certain if the turf areas were mechanically loosened prior to sod placement, or what type of fill was used in this area.

The USDA Web Soil Survey did not have recent information on the newly developed area. Most of the gravel pits have been removed.

The selected area at this site is an open field area next to a playground and the ponds. It is maintained annually by the City of Maple Grove. Visual Inspection did not reveal any major problems with turf establishment or plant growth. The only tree within the testing area is relatively small. The basis for this site selection was its unique construction history and assumed high level of compaction.

Chapter Five

Methods

5.1 Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (Ksat) was measured using the Modified Philip-Dunne Infiltrometer (MPD). This device is illustrated in Figure 5.1.1. An initial measurement of soil moisture content is taken near the MPD using the gravimetric measurement method (ASTM D2216-05, 2005). The device is then filled to the desired water level (typically between 30 and 50 cm of head). Once the device is filled, a stopwatch is started and head vs. time data is collected until the device has emptied or until such a time that measurements are not possible (MPD Manual, 2010). When data collection has ceased, a final moisture content sample is collected. Alternatively, a method used for estimating the final moisture is provided in the data analysis section.

The MPD uses a Green-Ampt model of infiltration that assumes a sharp wetting front from the infiltrating water. Parameters for the model use initial and final volumetric moisture content, Ksat, and C, the wetting front suction. A spreadsheet program, first developed by Nestingen (2007) and subsequently modified by additional researchers at St. Anthony Falls Laboratory, uses the head vs. time data and initial and final volumetric moisture content to predict the growth of a three-dimensional bulb of wetted soil formed as the result of the infiltrating water. The spreadsheet converts the head vs. time data to a cubic spline function, and then a regression model is used to fit the cubic curve by automatically varying Ksat and C.   The program outputs the values of Ksat and C that provide the best fits to the cubic spline function.

Figure 5.1.1 Illustration of the Modified Philip-Dunne Infiltrometer.

The MPD was used to measure the permeability of the soil at all three sites in this study. For the initial assessment of each site, 100-150 points of measurement were taken to characterize each site's ability to infiltrate stormwater. The measurements were spaced out using a 2 m by 5 m grid at Lake Minnetonka Regional Park and French Regional Park. Maple Lakes Park, a smaller site, used a 2 m by 3 m grid. These measurements were then used to determine where the soil remediation treatments should be applied at each site. This location was subdivided into two treatment plots and a control plot. The goal was to choose plot locations with similar values of relatively low Ksat.

Remediation was performed after the conclusion of the initial assessment of each site. To assess the effects of different remediation techniques, follow-up measurements of Ksat were taken on each plot at each site during the second summer of the study. For these follow-ups, 30 measurements were taken on each plot. The grid system used at Lake Minnetonka Regional Park was 3 m by 3 m, 2 m by 3 m for Maple Lakes Park, and 2 m by 3.5 m at French Regional Park. Different grid systems were used because the plot dimensions at each site were different.

French Regional Park and Maple Lakes Park were assessed during the spring of the third year of the study to determine the intra-annual variability of Ksat values and to determine if the compost was still viable. Measurements were taken at the same locations as the previous summer. Additional measurements of Ksat were taken on the control and compost plots later in the third summer at French Regional Park. This testing was performed to compare with measurements taken earlier to assess for seasonal change.

5.2 Soil Bulk Density

Bulk density is a direct measurement of soil compaction. Increased levels of soil compaction lead to increased levels of bulk density. Dry bulk density is measured by the ratio of the dry mass of soil per volume. A drive-cylinder sampler, purchased from ELE International, was used in accordance to the ASTM D-2937 standard (ASTM D2937, 2010). The sampler tube was driven into each location using a slide hammer. During the initial assessment of each site, measurements of bulk density were taken within the study area near MPD measurements to compare Ksat to bulk density (22-66 measurements per site). During the second summer (after remediation was performed), 6-9 bulk density measurements per site were taken at random locations on each of the plots for comparison in density level changes. The values of bulk density were also used to convert the gravimetric moisture content samples to volumetric moisture content, which is required for the MPD spreadsheet program.

5.3 Soil Strength

Soil strength is another direct measurement technique to assess soil strength. A digital hand-held penetrometer made by Eijelkamp was used to measure soil strength. The model was the Pentrologger (hardware v3.0, software v3.11). The penetrometer uses a small cone with known area attached to a rod and data logger. The cone is pushed into the ground at a specified rate. The cone had an area of 1 cm^2 with a cone angle of 30 degrees, and was pushed into the ground to a depth of 80 cm at 2 cm/s. A data logger collected the soil strength (measured in MPa) at 1 cm intervals. This same setup was used previously by researchers to quantify the level of soil compaction by wheel traffic (Ozgoz et al., 2006).

Three measurements within a 1 m radius were averaged at each measurement location. The penetrometer was used at nine locations on every plot at each site with one exception. The control plot at Lake Minnetonka Regional Park was too hard for the penetrometer to penetrate the ground without severely bending the rod, so no measurements are available for this plot. The level of moisture content of the soil can affect soil strength measurements. Care was taken to make sure that measurements were taken within a few days of each other and after recent rainfall to ensure that the soil moisture profile was more uniform throughout the depth.

5.4 Soil Coring

Soil cores were collected from each plot type at each site for comparison. Soil profiles were obtained from the surface to 36 inches below the surface using a soil auger. The Research Analytical Lab (RAL) at the University of Minnesota performed a soil texture analysis of nine soil samples. Soil samples measuring 150 grams in mass were taken from the 0-12" depth range from the soil cores. Each sample was sieved to remove particle sizes above 2 mm. RAL used the hydrometer method to determine the percent sand, silt, and clay found in each sample. The hydrometer method depends on Stokes' Law, which relates settling velocity to a particle size (Gee and Bauder, 1986). Particle sizes can then be related to a particular particle type: sand, silt, or clay. Each core was assigned a texture class based on the percentages of sand, silt, and clay using the Soil Texture Calculator on the Natural Resources Conservation Service's website, which uses the United States Department of Agriculture classification for soil texture (NRCS, 2010). In addition, photographs were taken of each core and field test methods were used to estimate the soil texture and color at different locations within a soil core (See Appendix A).

5.5 Site Setup

An initial assessment of the saturated hydraulic conductivity and bulk density of each site was conducted in the summer of 2008 to determine the level of compaction. At the conclusion of these measurements a subarea in each site was divided into three plots: control, till, and compost. Initially, the plots were subdivided to provide comparable values of saturated hydraulic conductivity between each plot. Areas, uninterrupted by trees, were preferred for the subsoiler to perform deep-tillage. The subsoiler had to work outside of the crown of a given tree. It also had to avoid underground utilities. Consideration for the access of the remediation equipment was thus the ultimate determinator of plot size and location.

5.6 Soil Remediation Techniques

Soil remediation was performed by the Three Rivers Park District Forestry and Maintenance staff in October 2008 after the conclusion of the initial assessment measurements. One control plot and two treatment plots were established within the study area at each site. The control plot did not receive any treatment so that it could be compared with the treatment plots in follow-up measurements. The first treatment plot, referred to as the “till” plot was remediated using deep-tillage and a tree-spading machine. Deep-tillage was conducted by using a subsoiler with two-foot long tines. This machine used larger rubber tires to minimize soil compaction. Ripping was spaced at 12” intervals to approximately a 22”-24” depth. The tree-spading machine was used to comingle the soil to a depth of 16” to 18”. The other plot was labeled the “compost” plot. This plot was remediated identically to the till plot, but before spading, an average of three inches of compost was added to the soil surface. The compost consisted of yard-waste and was provided by Plaisted, Inc. Details of the compost composition can be found in Appendix A. The treatment plots were then smoothed with a Harley Rake. The plots were dormant seeded and fenced off from the surrounding area.

Chapter Six

Data Analysis

6.1 Wetting Front Suction Correction

The MPD spreadsheet program optimizes the fit of the predicted to measured head discharge curves in the infiltrometer by changing the saturated hydraulic conductivity (Ksat) and wetting front suction (C). Values for C vary between soil texture classes. Typical values are between -0.97 cm (Sand) and -156.5 cm (Clay) (Rawls et al., 1983). The spreadsheet program outputs a negative C value for soils that are hydrophilic and positive values for soils that are hydrophobic. It was found during the testing of the MPD device that C values are not particularly sensitive to the regression model used to fit the head vs. time data. This can result in C values that are positive. Regalado et al. (2005) discarded data with positive C values when analyzing the Philip-Dunne Permeameter, the device that the MPD is modified from originally.

In one study of hydrophobic soils (both constructed and naturally occurring) Bauters et al. (2000) found that water repellant sands may have wetting front suction values up to 9 cm. Ahmed (2010) found that if a MPD is placed in a highly permeable soil (sand) that is surrounded by a much lower permeable soil (silt), a positive C value (~24 cm) could be found.

To allow for positive C values, a range was set in the MPD spreadsheet program that limited extreme values. The allowable range was -150 cm < C < 10 cm.

6.2 Soil Moisture Content

Gravimetric sampling was used to measure the moisture content by mass for the initial and final moisture contents of the soil used for the MPD measurements. The difference, $\Delta\theta = \theta_f - \theta_i$, where θ_f = final moisture content and θ_i = the initial moisture content, is input into the MPD spreadsheet program. Bulk density samples were taken to convert the moisture content to volumetric moisture content, which is used in the MPD spreadsheet program. The conversion from gravimetric moisture content to volumetric moisture content is:

$$\theta_v = (\rho_b / \rho_w)\, \theta_g \qquad (6.2.1)$$

where,

θ_v is the volumetric moisture content [cm^3/cm^3]

θ_g is the gravimetric moisture content [g/g]

ρ_b is the dry bulk density of the soil [g/cm^3]

ρ_w is the density of water [g/cm^3]

Initial moisture contents were found by taking a gravimetric moisture sample just below the surface of the soil near the MPD measurement location. The final moisture content is taken underneath the location of the MPD at the end of the experiment. In some cases, higher than expected volumetric moisture contents were found in final moisture content samples and were not considered accurate. The soil beneath the MPD becomes fully saturated, which can create a "muddy" soil. Taking moisture samples from this mud can lead to excessive volumetric moisture contents (> 60% moisture content by volume). Collection of an initial moisture content sample is simple and a reasonable estimate of final moisture content will suffice to determine $\Delta\theta$. The method for making this estimate is presented in the next paragraphs.

Since the MPD spreadsheet uses a Green-Ampt infiltration model, which assumes a sharp wetting front, the final moisture content may be assumed to be at its fully saturated condition. The saturated moisture content may be estimated as the porosity of the soil. Actual field saturation will be less than the porosity due to entrained air, but this should be a useful estimation. The porosity of a soil is determined by the following relationship:

$$\theta_s = \eta = 1 - (\rho_b/\rho_p) \quad (6.2.2)$$

where,

θ_s is the saturated volumetric moisture content [cm^3/cm^3]

η is the porosity of the soil

ρ_p is the particle density of the soil material [g/cm^3]

The bulk density of the soil was found for each site (see Chapter Five) and the particle density was estimated based on the amount of mineral matter and organic matter expected to be present in the soil. Organic matter content was not measured, but reasonable estimations were made. The control and tilled plots were estimated to be approximately 95% mineral matter and 5% organic matter. The compost plots were estimated to have approximately 19% organic matter, which was determined by taking the depth of the compost layered on top of the soil divided by the depth of incorporation into the soil (3" of compost was spaded into ~16" depth range). Using these ratios of mineral and organic matter the effective particle density was estimated from equation 6.2.3 (Jury and Horton, 2004), which assumes densities for mineral matter (2.56 g/cm^3) and organic matter (1.30 g/cm^3).

$$\rho_{particle} = 2.65X_{\min} + 1.3X_{OM} \qquad (6.2.3)$$

$$1 = X_{\min} + X_{OM} \qquad (6.2.4)$$

where,

$X_{\min}$ is the fraction of mineral matter found in the soil

X_{OM} is the fraction of organic matter found in the soil

Using these estimates provided the following saturated moisture contents for each site:

Table 6.2.1 Saturated moisture contents (by volume fraction).

Location:	θ_{sat}
French Regional Park	
Pre-remediation	0.45
Control Plot (years 2 & 3)	0.44
Till Plot (years 2 & 3)	0.45
Compost Plot (years 2 & 3)	0.52
Lake Minnetonka Regional Park	
Pre-remediation	0.43
Control Plot (year 2)	0.38
Till Plot (year 2)	0.43
Compost Plot (year 2)	0.53
Maple Lakes Park	
Pre-remediation	0.46
Control Plot (years 2 & 3)	0.43
Till Plot (years 2 & 3)	0.48
Compost Plot (years 2 & 3)	0.61

These moisture contents were used as the final moisture contents for the MPDs at their respective locations. It was found by researchers analyzing the Philip-Dunne Permeameter, that the change in moisture content ($\Delta\theta$) had a very little effect in the sensitivity of saturated hydraulic conductivity (Regalado et al., 2005).

6.3 Determination of Probability Distribution Model

A probability distribution model is necessary in performing statistical analyses of the data. Values for saturated hydraulic conductivity (Ksat) may be described with a lognormal distribution (Asleson, 2007; Munoz-Carpena, 2002). To find how well the Ksat data acquired in this study fits a lognormal model, the Kolmogorov-Smirnov Test (K-S Test) was used to determine the goodness-of-fit. This test compares the cumulative density function (CDF) of an assumed theoretical distribution of data with an experimental cumulative frequency, which is found empirically (Ang and Tang, 2007). The maximum difference between the two frequencies is used to determine the goodness-of-fit. If the maximum difference is larger than what is expected at a certain significance level, then the model is rejected. The procedure, given by Ang and Tang (2007), was used to determine the probability distribution models for Ksat values within the experimental plot locations. For comparison, normal and lognormal distribution models were used.

6.3.1 Kolmogorov-Smirnov Test Procedure

Arrange observed data in ascending order.

Using the ordered data (x_1, x_2,…,x_n), develop a stepwise experimental frequency function:

$$Sn(x) = 0 \text{ for } x < x_1 \quad (6.3.1)$$

$$= k/n \text{ for } x_k \leq x \leq x_{k+1}$$

$$= 1 \text{ for } x \geq x_n$$

where,

k = rank

n = sample size

Let F_x (x) be the theoretical CDF of the chosen probability distribution model. To measure the maximum difference between the experimental frequency and the CDF of theoretical probability model, let:

$$D_n = \max|F_x(x) - S_n(x)| \quad (6.3.2)$$

D_n is compared to a critical value of D_n called $D_{n,alpha}$

$$P(D_n \leq D_{n,\alpha}) = 1 - \alpha \quad (6.3.3)$$

where,

α = significance level

If D_n is less than $D_{n,\alpha}$ for a specified significance level, then the theoretical probability distribution model may be accepted, else rejected. Values for $D_{n,\alpha}$ can be found tabulated in probability textbooks, or may be found tabulated online. $D_{n,\alpha}$ is dependent on the number of observations and the significance level used.

6.3.2 Results

All study areas at each site were found to be distributed lognormally at a significance level of 0.01 or higher. A normal distribution was only significant to a level of 0.01 at French Regional Park. Maple Grove showed the strongest agreement with a lognormal distribution (at a significance level of 0.10). These results are tabulated in Table 6.3.1. The theoretical model frequencies were plotted against the experimental frequency. For these plots see Figures 6.3.1 to 6.3.3. A 45^{o} line is drawn, which represents how a perfect agreement between the theoretical frequency and the experimental frequency would look.

Table 6.3.1 Kolmogorov-Smirnov Test results.

	Maximum Significance Level	
Site:	Normal Distribution	Lognormal Distribution
Lake Minnetonka Reg. Park	n/a	0.01
French Reg. Park	0.01	0.01
Maple Lakes Park	n/a	0.10

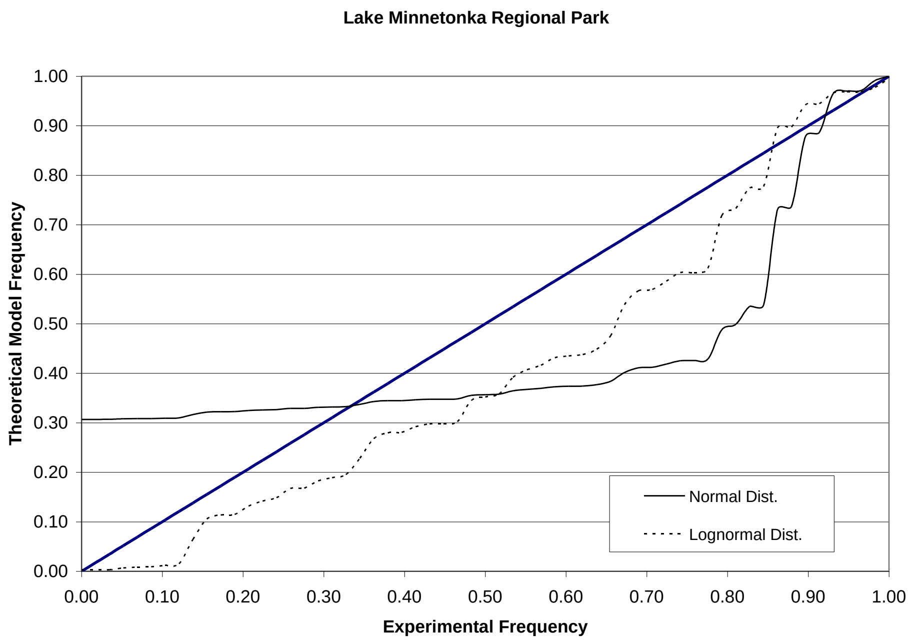

Figure 6.3.1 Theoretical Model Freq. vs. Experimental Freq. for Lake Minnetonka Regional Park.

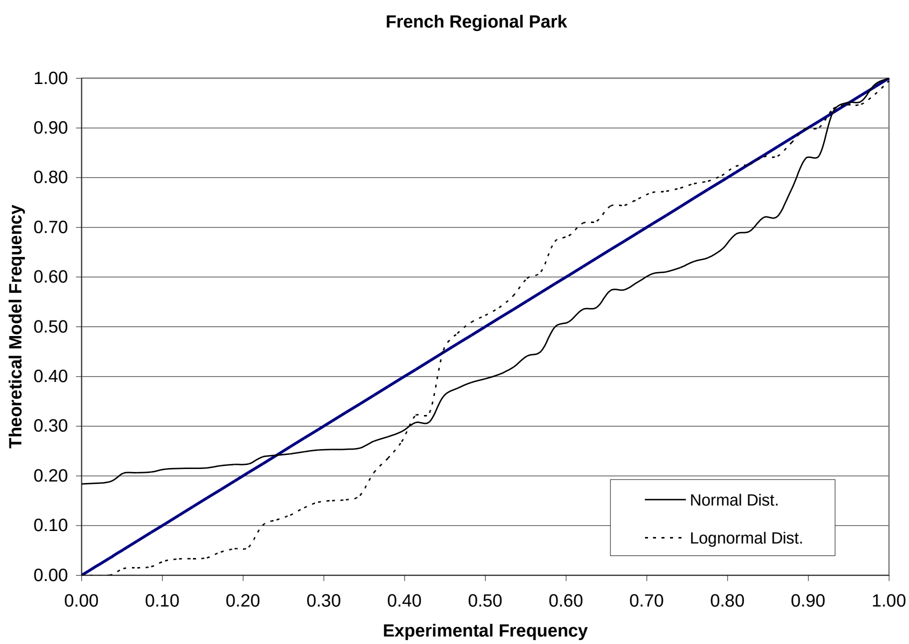

Figure 6.3.2 Theoretical Model Freq. vs. Experimental Freq. for French Regional Park.

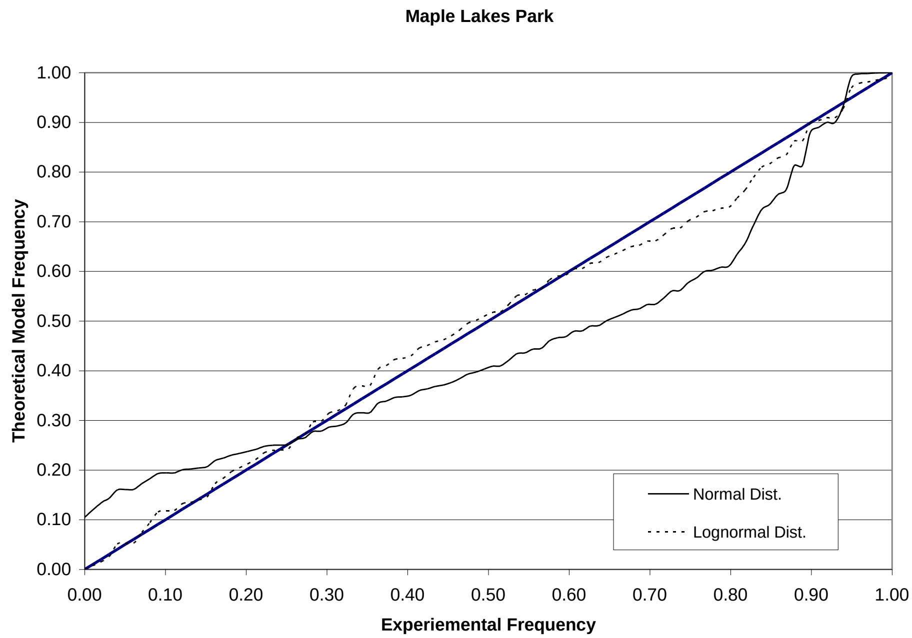

Figure 6.3.3 Theoretical Model Freq. vs. Experimental Freq. for Maple Lakes Park.

6.4 Treatment of Outliers

A methodology was developed to remove outliers from saturated hydraulic conductivity data. Outliers are defined herein as measured values that are unrepresentative of the actual distribution. The measured saturated hydraulic conductivity varies over several orders of magnitude, and it is possible that one measurement could distort the measured mean and distribution. This required modifying the Modified Philip-Dunne Infiltrometer spreadsheet program to include a measure of error (difference from measurements) in predicting the head vs. time data. A robust method was then used to determine the acceptable level of error.

6.4.1 Normalized Error

The MPD spreadsheet program determines the saturated hydraulic conductivity (Ksat) and wetting front suction (C). First the spreadsheet fits a cubic spline fit of the original head vs. time data, which is used to give a more accurate gradient of the head vs. time data. Then it minimizes the root mean square (rms) of the difference between spline fitted time increment (Δt) and predicted time increment as well as spline fitted head increment (ΔH) and predicted head increment, by adjusting the values for Ksat and C. Solver, in Excel, has been used to find the best fitting values of Ksat and C for which the rms error of Δt or ΔH will be minimum. Prior to the wetted front reaching a minimal radius ($\sqrt{r_1^2 + L_{\max}^2}$, where r_1= radius of the MPD, L_{max}= depth of insertion into the soil), the head versus time data are neglected from the analysis because the geometry of the wetting front changes, requiring a different series of equations. Two sets of Ksat and C are obtained, one by optimizing the Δt and the other by optimizing ΔH. Using each set of final Ksat and C values the spreadsheet determines the predicted time for the corresponding water level and it plots both the predicted and cubic spline head vs time curve.

To determine how well the optimized curves fit the cubic spline curve, a normalized error was created. The error is found by taking the sum of the RMS errors of regression (units are in seconds) for each of the Δt and ΔH optimizations and dividing by the length of time being used by the optimization routine (the ending time of the measurements minus the time at which the optimization routine starts). The normalized error is now an output of the MPD spreadsheet program and is used to determine the optimized curve (Δt or ΔH) that best fits the cubic spline curve. The Ksat and C values for which this normalized error is the lowest will be selected. This normalized error can then be used to determine outliers in the data set.

6.4.2 Outlier Removal

An outlier removal technique was used to determine the acceptable level of error. Data with normalized errors above the limit specified by the outlier removal technique were then discarded. The first two years of data from the plots at all sites was used as the dataset to determine the acceptable level of error.

To remove outliers in the dataset, a technique that did not use the average and standard deviation of the data set to remove outliers, since one outlier can significantly change the value of these parameters (Urban et al., 2001). The method uses the median and the deviation from the median to allow several outliers to be removed from the data set, as outlined in Wadsworth (1990).

<u>Procedure:</u>

The normalized errors of approximately 490 measurements were tabulated. The normalized error data was found to be close to a lognormal distribution. The data was then sorted in ascending order. The median of data, T, was calculated. A column next to the data found the absolute difference between the error value and the median value. The median of these values was then calculated. An estimator of the scale, S, was calculated:

$$S = 1.483 \times \text{median}_{i=1,\ldots,n} \left| E_i - T \right| \qquad (6.4.1)$$

where, 1.483 is a correction factor used to correlate S to the standard deviation, σ, of a normal distribution (Urban et al. 2001). Each error value was then given a z-score:

$$z_i = \frac{E_i - T}{S} \qquad (6.4.2)$$

Any error that had a z-score greater than 1.96 is considered an outlier for the 95% confidence level. Normalized errors found to be above 0.25 were subsequently removed from the dataset, which accounted for about 3% of the measurements.   Z-scores that were less than -1.96 were kept because they represent very low errors.

6.5 Comparison of Plot Types

6.5.1. Study Area Division

Each site was initially assessed with 100-150 measurements of saturated hydraulic conductivity (Ksat) during the first summer of this study. At the conclusion of these measurements, a smaller area (designated as the "study area") within the site was chosen for the location of the three plots: control (C), till (T), and compost (P). This area was equally divided between the plot types. Due to the restrictions by the subsoiler used to perform the deep tillage and the amount of compost available to the project, the location and size of the study area was limited. This meant that an equal number of measurements between plots were not possible and some plots had a low number of usable measurements. To correct for this, the measurements on the plots during year one of the study were combined to form one control plot (C_{all}= C1+T1+P1). Measurements taken during the second year of the study on the individual plots were then compared to the year one control (i.e. C1 vs T2, C1 vs P2). This setup was used at French and Lake Minnetonka Regional Parks (See Figure 6.5.1). The number of measurements was adequate at Maple Lakes Park to compare individual plots between years.

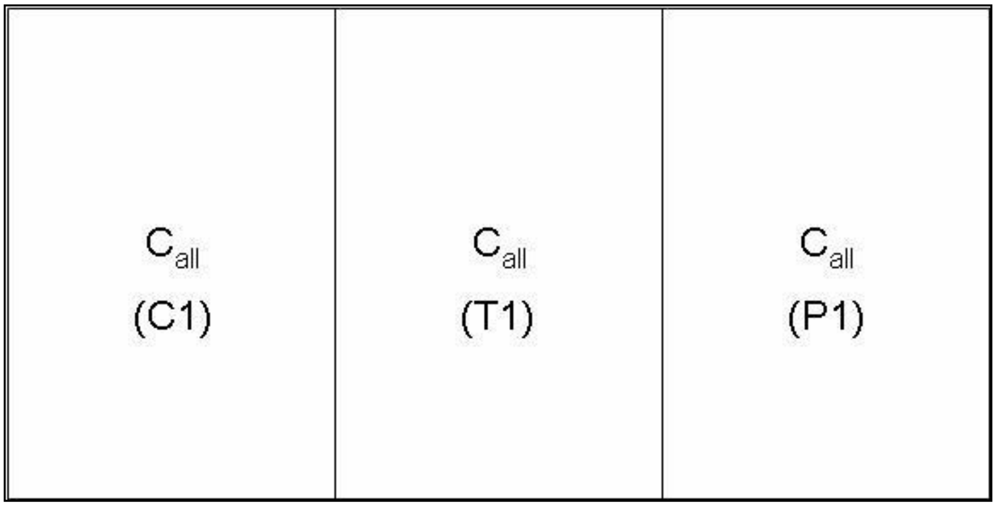

Figure 6.5.1 Plot setups. **The study area was subdivided into three plot types during the first year before remediation. Setup for Maple Lakes Park is in parentheses.**

Figure 6.5.2 shows the set up used during the second summer after remediation had taken places on the treatment plots.

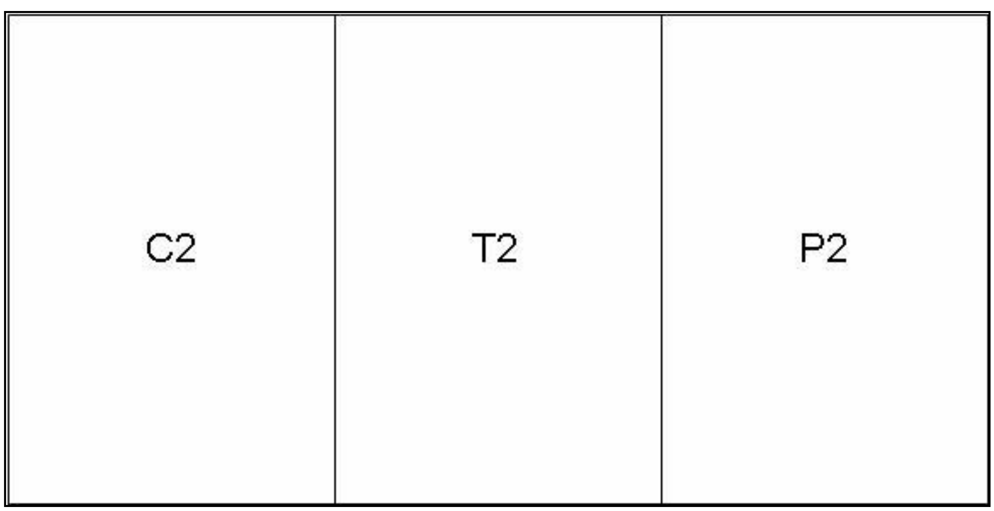

Figure 6.5.2 Designation of the plots during the second year (all sites).

6.5.2 Two-Sample t Significance Test

A two-sample t significance test was used to verify that the plot divisions within the study area during year one had means for Ksat that were not statistically different. This t test was also used to verify that the means of the control plots between subsequent years were also not statistically different. Finally, the t test was used to show that the treatment plots were statistically different from the control plots, which would indicate that the treatment had provided some benefit. The test procedure was adapted from Moore and McCabe (2004).

6.5.3 t-Test Procedure

It was previously found that a lognormal distribution was a good fit of the Ksat data. Because the t-test assumes a normal distribution, the natural log of the data was taken. The means of two different samples are taken (in this case a sample refers to the set of measurements in a plot). Next, a t statistic is calculated:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \qquad (6.5.1)$$

where,

$\bar{x}$ is the mean of the sample population

s^2 is the variance of the sample population

n is the population size of the sample

The probability of t occurring is determined by the degrees of freedom. A computer program is often used to determine P ($T \geq t$), the probability that a certain value T, exceeds the test statistic. A data analysis tool package that can run a two-sample t-test assuming unequal variances was used, which outputs values for the one-sided probability of $T \geq t$.

A hypothesis test is used to determine if the means (μ) between the populations are statistical different or not:

$$H_o : \mu_1 = \mu_2$$
$$H_A : \mu_1 \neq \mu_2 \qquad (6.5.2)$$

If P ($T \geq t$) is greater than the test significance level (alpha) than there is insufficient evidence to reject the null hypothesis (H_o) and the means of the plots are found to be equal. If the opposite is true, the alternative hypothesis (H_A) must be accepted, which states that the means are statistically different.

6.5.4 Results of the t-Test

A significance level of 0.01 was used for the t-tests. The measurements within the study area were combined and then compared to the measurements found in the individual plot sections. It was found at French and Lake Minnetonka Regional Parks that the means between the combined measurements and the different plots were statistically similar (See Tables 6.5.1-2). This allows more measurements to be used to compare with the second year measurements. For example, the C1 plot at Lake Minnetonka only had 14 acceptable MPD measurements and the following year 29 measurements were obtained (C2). Because C1, T1, and P1 could be combined into Call, C2 can be compared to 58 measurements.

Table 6.5.1 French Regional Park t-Test results.

Sample Comparison	$P(T \geq t)$	H_o
C_{all} vs. C1	0.026	Accept. Means are equal
C_{all} vs. T1	0.242	Accept. Means are equal
C_{all} vs. P1	0.221	Accept. Means are equal

Table 6.5.2 Lake Minnetonka Regional Park t-Test results.

Sample Comparison	$P(T \geq t)$	H_o
C_{all} vs. C1	0.251	Accept. Means are equal
C_{all} vs. T1	0.278	Accept. Means are equal
C_{all} vs. P1	0.486	Accept. Means are equal

The individual plots were not statistically similar at Maple Lakes Park (See Table 6.5.3). Plots were compared to each other between years and not to C_{all}.

Table 6.5.3 Maple Lakes Park t-Test results.

Sample Comparison	$P(T \geq t)$	H_o
C_{all} vs. C1	0.000	Reject. Means are not equal.
C_{all} vs. T1	0.381	Accept. Means are equal
C_{all} vs. P1	0.001	Reject. Means are not equal.

The t-tests were also performed to compare the control plots between years. They were also used to compare the treatment plots to the control plots. These results are given in the next chapter.

6.6 f-test for comparison of soil variability

The variances of pre-remediation control areas were compared with the variances of post-remediation plots. Comparisons of the variances were made to determine if pre-remediation variability of saturated hydraulic conductivity can predict the effectiveness of soil remediation techniques. The hypothesis is that highly variable soils may have a more established network of natural pathways (i.e. macropores), which creates areas of high conductivity. If deep tillage occurs on these highly variable soils it may cause the saturated conductivity to decrease. The f-test procedure was adapted from Moore and McCabe (2004).

The f-test is used to compare the variances between two populations. Because the f-test assumes a normal distribution, the natural log of the data was taken. The variances of two different samples are taken (in this case a sample refers to the set of measurements in a plot). Next, a f statistic is calculated:

$$f = s_1^2/s_2^2 \qquad (6.6.1)$$

where,

s^2 is the variance of the sample population,

The probability of f occurring is determined by the degrees of freedom in the numerator and denominator. A computer program is often used to determine P ($F \geq f$), the probability that a certain value F, exceeds the test statistic. A data analysis tool package was used, which outputs values for the one-sided probability of $F \geq f$. The probabilities were double to determine the two-sided cases.

A hypothesis test is used to determine if the standard deviations (s) between the populations are statistical different or not:

$$H_o : s_1 = s_2$$
$$H_A : s_1 \neq s_2 \qquad (6.6.2)$$

If P (F $\geq$ f) is greater than the test significance level (alpha) than there is insufficient evidence to reject the null hypothesis (H_o) and the standard deviations of the populations are found to be equal. If the opposite is true, the alternative hypothesis (H_A) must be accepted, which states that the standard deviations are statistically different. An alpha value equal to 0.05 was chosen and the results of these tests are given in the next chapter.

Chapter Seven

Results and Discussion

7.1 Saturated Hydraulic Conductivity

Summaries of the saturated hydraulic conductivity (Ksat) measurements are discussed by site. Year one measurements represent the site before the individual plots were treated with the soil remediation techniques outlined in Chapter Four. Year two measurements took place the following summer after the plots had been remediated. Measurements were taken during the third year of the study at Clifton E. French Regional Park and Maple Lakes Park. The “geomean” listed in summary tables is the geometric mean of the data, which is the value used to compare the effectiveness of the soil amendments. The geometric mean is similar to the mean of the log of Ksat measurements. This emphasizes the exponent of the Ksat instead of the actual numeric value to achieve a more equal weight of the low Ksat values in the final mean. The Ksat data is also represented by ArcGIS © figures that show the spatial variability of Ksat values. Outliers were removed from the summary data and figures.

7.1.1 Clifton E. French Regional Park

The initial testing at French Regional Park revealed that there was a large amount of variability across the site; over three orders of magnitude of difference between Ksat values were observed (See Figure 7.1.1). The highest Ksat values were observed near trees and in the southwest section of the study area. This southwest area had very loose and aggregated soil near the surface. The location for the plots was chosen to be located northeast of this area, which had lower observed Ksat values, less variability, and less interference from trees. Table 7.1.1 summarizes the pre-remediation Ksat values.

Table 7.1.1 Clifton E. French Regional Park: year one results.

	Clifton E. French Regional Park Year One, Pre-Remediation			
Plot:	Control	Till	Compost	*Combined
# Measurements	17	23	18	58
Average [cm/hr]	3.78	9.13	8.84	7.47
St. Dev [cm/hr]	4.24	10.44	7.05	8.23
COV	1.12	1.14	0.80	1.10
Geomean [cm/hr]	2.26	5.10	5.46	4.10

*Measurements from all three plots were combined for comparison to post-remediation values. Please refer to Chapter Six for further explanation.

A total of fifty-eight measurements were combined to form a control area to compare with post-remediation data. This control area had a geometric mean of 4.10 cm/hr with a coefficient of variation of 1.10. The geometric mean of the data was close to the findings of other soil compaction studies discussed in Chapter Two (See Table 2.4.1). It is expected that the soil in this area is compact and may benefit from soil remediation.

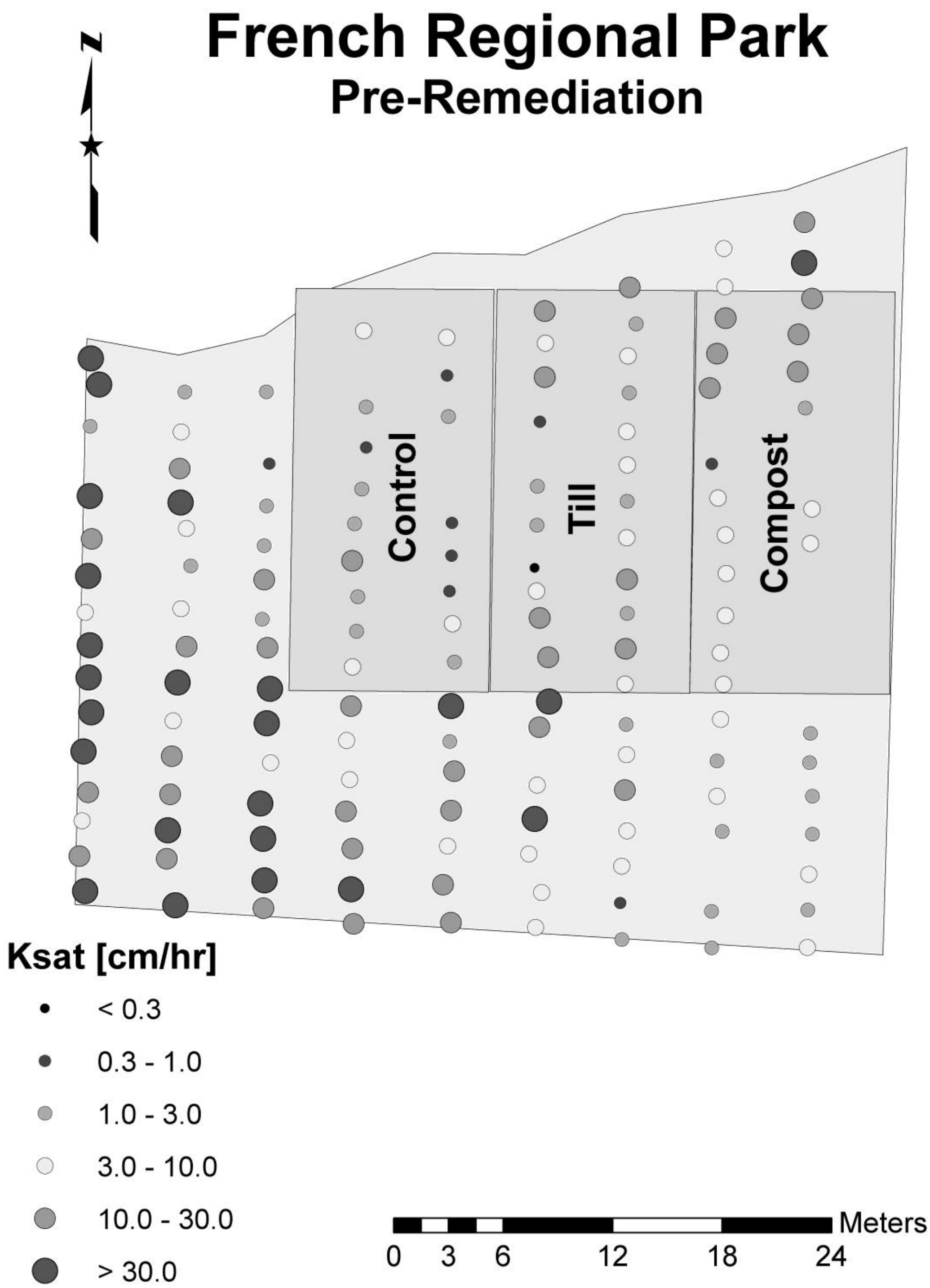

Figure 7.1.1 The spatial variability of Ksat at Clifton E. French Regional Park (pre-remediation).

Soil remediation was performed during Fall 2008 on the treatment plots. In Summer 2009, follow-up measurements of Ksat were taken on each plot type (See Figure 7.1.2). Testing revealed that there was an increase in the number of highly permeable areas in the control and compost plots. The control plot had more Ksat values in the > 30 cm/hr level than the compost plot, but had fewer in the 10-30 cm/hr range than the compost plot. The till plot Ksat values were similar to the previous year. The post-remediation results during the second year of testing are summarized in Table 7.1.2.

Table 7.1.2 Clifton E. French Regional Park: year two results.

	Clifton E. French Regional Park Year Two		
Plot:	Control	Till	Compost
# Measurements	29	29	29
Average [cm/hr]	17.08	7.04	18.47
St. Dev [cm/hr]	17.85	5.88	15.05
COV	1.05	0.84	0.81
Geomean [cm/hr]	9.37	5.36	13.76

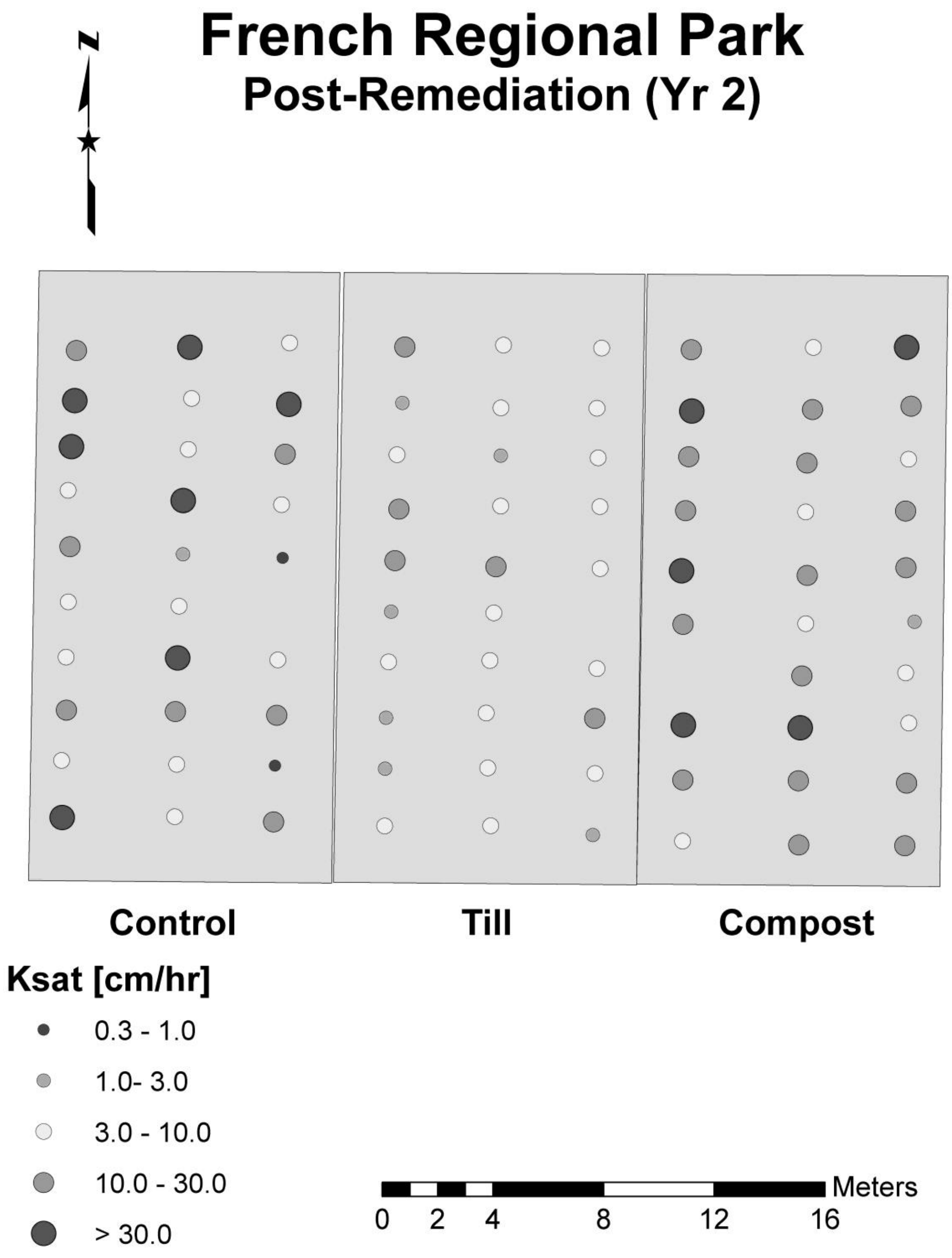

Figure 7.1.2 The spatial variability of Ksat at Clifton E. French Regional Park (year two, post-remediation).

The results of the post-remediation testing at French Regional Park show large differences in Ksat in the control and compost plots between the two years. The geometric mean of the control plot was 2.29 times the geometric mean of the control area of the previous year and was statistically different ($P \approx 0.003$). This may be due to seasonal variation in the soil. Plot comparisons will be made within the same year, since they cannot be compared between years. The till plot's geometric mean was three-fifths of the Ksat geometric mean in the control plot. The mean on the till plot was not statistically different ($P \approx 0.02$) from the mean of the control plot. The geometric mean of the compost plot was 13.76 cm/hr; the highest of the three plots and 1.5 times as permeable as the control plot. However, the mean of the compost plot was not statistically different from the mean of the control plot ($P \approx 0.08$). The f-test results show that the till and compost plots were significantly less variable than the pre-remediation control area ($P = 0.002$ and $P = 0.014$, respectively).

Even though the compost plot had the highest infiltration capacity and level of improvement, its effectiveness is masked by the large change in Ksat in the control plot and the large covariance in all plots. It is hypothesized that there are changes in the soil structure due to seasonal variation, which can affect the permeability. To determine if the large changes in Ksat for the two plots were due to temporal effects a third year of testing was performed. Measurements were taken all plots during the spring (April and May). Another round of testing was performed in the middle of summer (August), but was limited to the control and compost plots. The third year testing results are shown in Figures 7.1.3 and 7.1.4. Ksat values are summarized in Tables 7.1.3, 7.1.4.

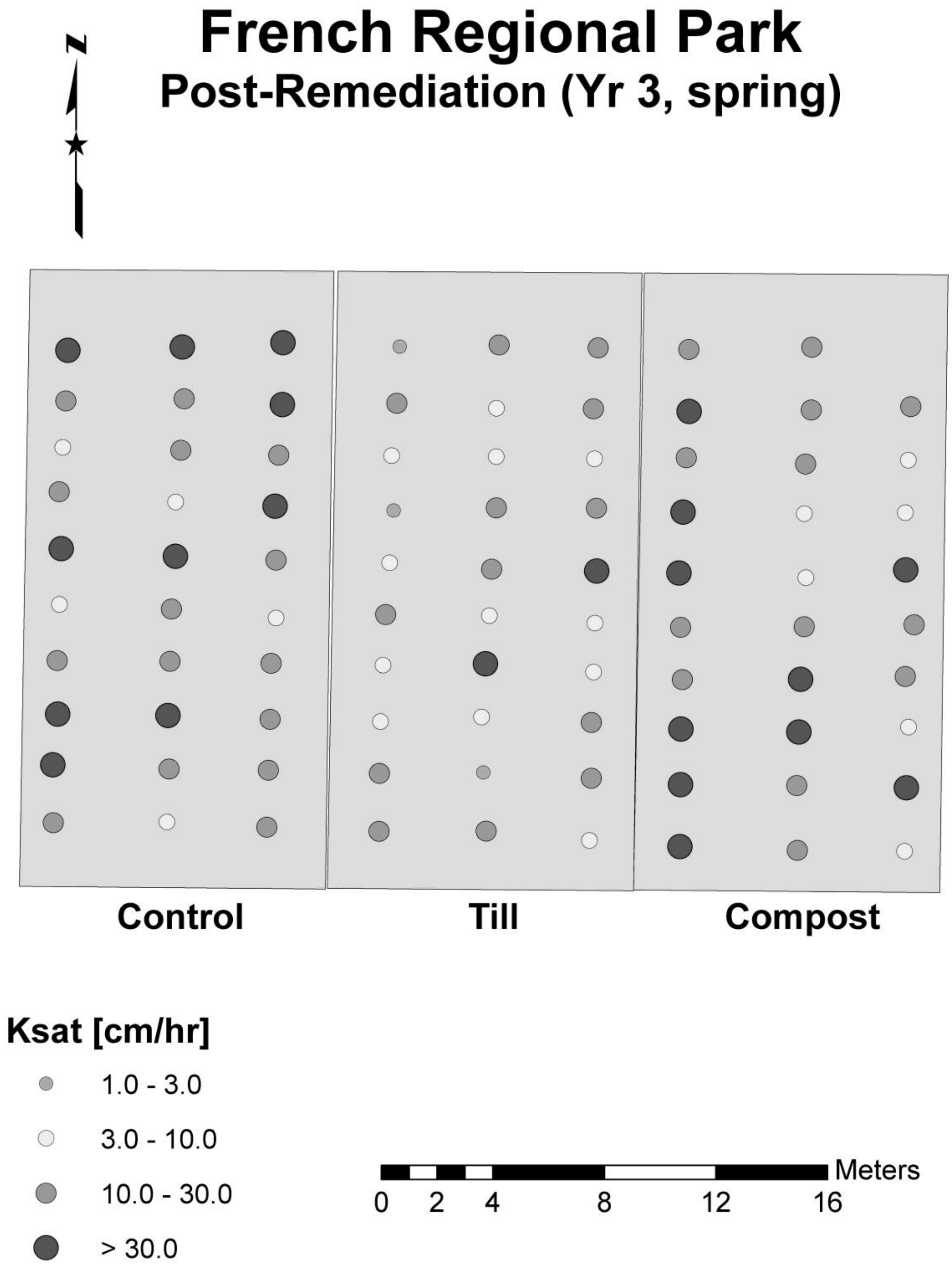

Figure 7.1.3 The spatial variability of Ksat at Clifton E. French Regional Park (year three, spring).

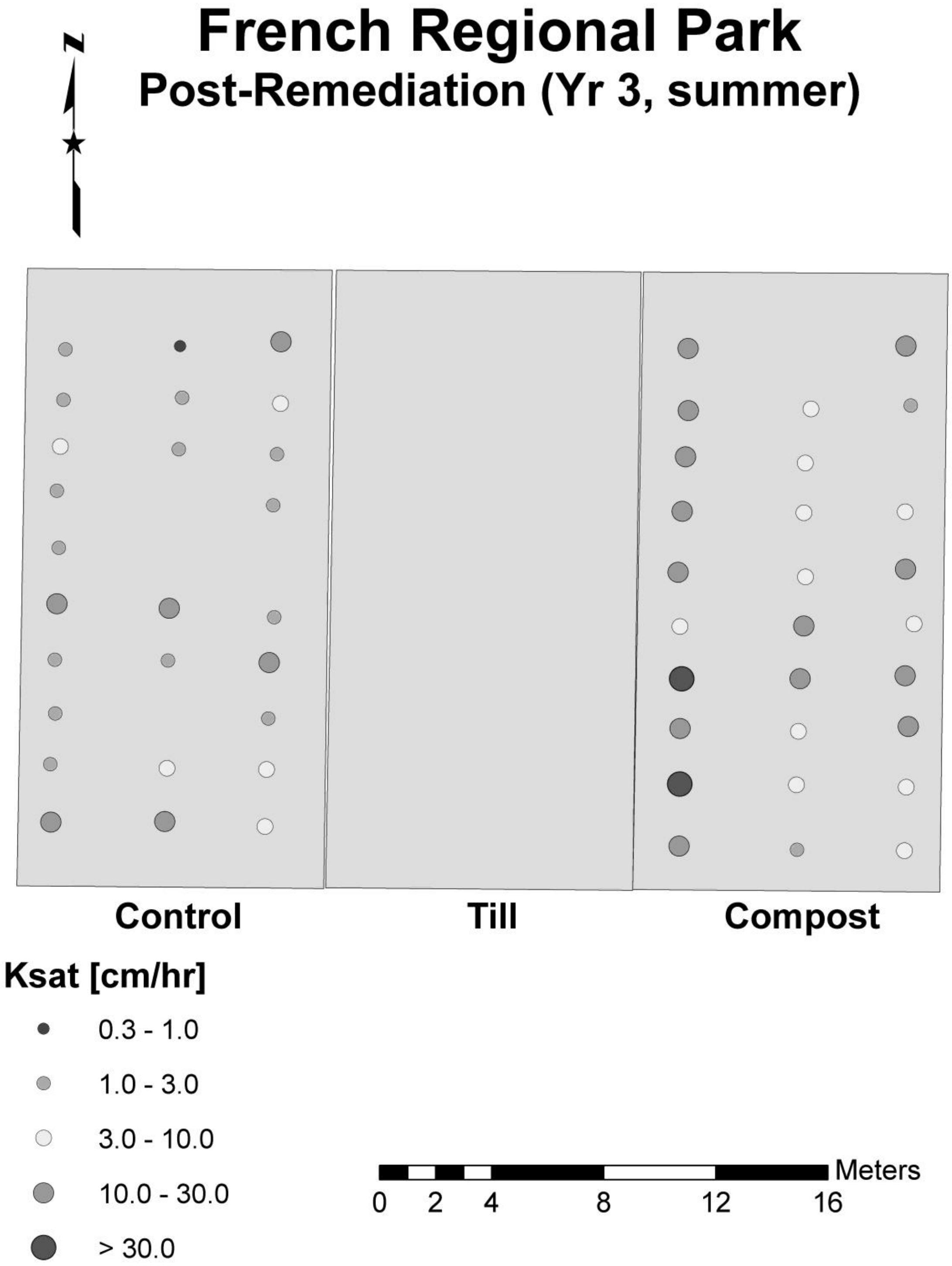

Figure 7.1.4 The spatial variability of Ksat at Clifton E. French Regional Park (year three, summer).

Table 7.1.3 Clifton E. French Regional Park: year three (spring) results.

	Clifton E. French Regional Park Year Three (Spring)		
Plot:	Control	Till	Compost
# Measurements	30	30	29
Average [cm/hr]	22.76	12.71	30.74
St. Dev [cm/hr]	14.40	10.12	26.99
COV	0.63	0.80	0.88
Geomean [cm/hr]	18.04	9.05	22.14

Table 7.1.4 Clifton E. French Regional Park: year three (summer) results.

	Clifton E. French Regional Park Year Three (Summer)		
Plot:	Control	Till	Compost
# Measurements	26	n/a	28
Average [cm/hr]	5.97	n/a	13.30
St. Dev [cm/hr]	6.67	n/a	10.68
COV	1.17	n/a	0.80
Geomean [cm/hr]	3.60	n/a	9.58

Differences in the number of highly permeable locations can be observed between year two measurements and the measurements taken during the spring of the third year (See Figures 7.1.2 and 7.1.3). These Ksat values were observed to be 1.61-1.93 times the values of the measurements taken the previous year. The till plot increased in permeability from the previous year, but had half the Ksat geometric mean of the control plot. Ksat was still highest on the compost plot, which had a Ksat of 22.14 cm/hr, but this was only 1.2 times the control plot geometric mean. All three plots had the largest

Ksat geometric means found for any year and any site during this round of testing. These values suggest that French Regional Park may not be considered compacted during the spring time.

Testing of the control and compost plot was completed once more later in the summer. A large difference can be seen between Figures 7.1.3 and 7.1.4. The number of highly permeable areas dramatically decreased in both plots between the spring and summer. Table 7.1.4 shows that the Ksat geometric mean of the control plot dropped to 3.60 cm/hr. This is approximately one-fifth of the value found during the spring testing. The compost plot also had decreased infiltration capacity. Its geometric mean was found to be 9.58 cm/hr, which was two-fifths of the value observed that spring. The compost plot did prove to still be effective over the course of the study. Even though this was the lowest compost geometric mean observed during the post-remediation testing, it was still 2.7 times the value of the control plot during the summer testing. The compost mean was significantly different than the control plot mean ($P << 0.01$).

The testing at French Regional Park showed great variability in Ksat on the control plot over the season and between years. The large changes in Ksat may be due to seasonal effects such as freezing and thawing. In a study using silt and clay soils, researchers found that after a freeze/thaw cycle, the permeability of the soil could change by up to two orders of magnitude (Chamberlain and Gow, 1979). The permeability is increased from vertical fissures left by thawing ice (Chamberlain and Gow, 1979). French Regional Park may have been more susceptible to this natural process because of its higher water table (due to the proximity of a lagoon). The till plot did not show any statistical improvement in permeability. During the spring in the third year, the geometric mean was approximately half that of the control plot. Tilling may have damaged the soils ability to infiltrate stormwater by destroying the natural channels and porosity that existed before remediation. The compost plot was effective at improving the permeability at this site. Because of the large seasonal and annual variability in Ksat from one plot, the Ksat values may only be compared between plots, with measurements taken at close to the same time, and not between either seasons or years.

7.1.2 Lake Minnetonka Regional Park

The initial assessment of Lake Minnetonka Regional Park revealed a high level of spatial variability (See Figure 7.1.5). Values of Ksat could vary up to two orders of magnitude within a couple of meters. Some of the highest Ksat values were found near the location of trees. Before the soil remediation techniques were performed, the location of the plots was established in the southwest section of the area measured. This location was selected to minimize the interference from trees. Ksat values for the pre-remediation plot areas are summarized in Table 7.1.5.

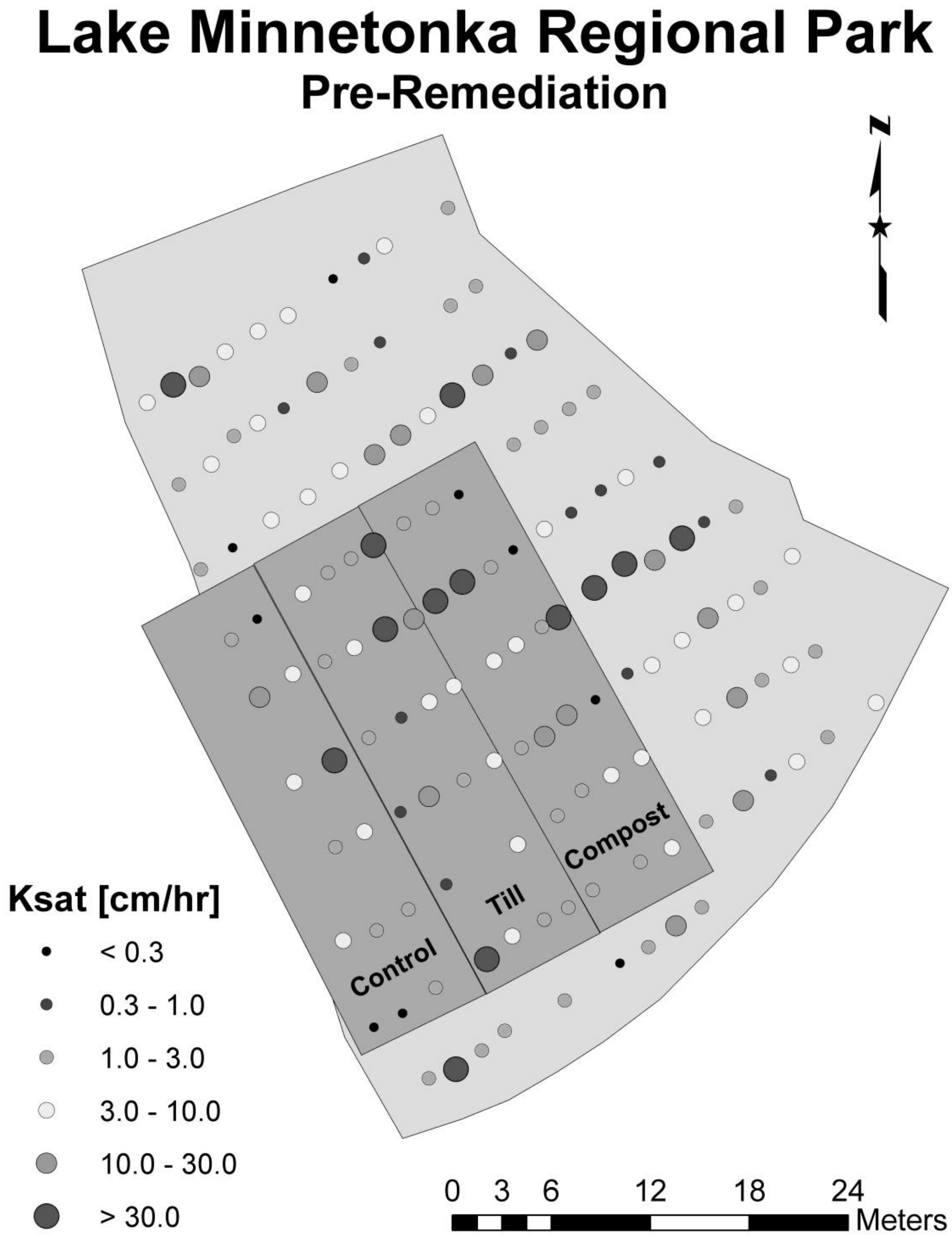

Figure 7.1.5 The spatial variability of Ksat at Lake Minnetonka Regional Park (pre-remediation).

Table 7.1.5 Lake Minnetonka Regional Park: year one results.

	Lake Minnetonka Regional Park Year One, Pre-Remediation			
Plot:	Control	Till	Compost	*Combined
# Measurements	14	21	23	58
Average [cm/hr]	7.25	10.01	12.34	10.27
St. Dev [cm/hr]	12.73	16.18	26.40	20.05
COV	1.76	1.62	2.14	1.95
Geomean [cm/hr]	2.29	3.98	3.27	3.22

*Measurements from all three plots were combined for comparison to post-remediation values. Please refer to Chapter Six for further explanation.

A total of fifty-eight measurements were combined to form a control area to compare with post-remediation data. This control area had a geometric mean of 3.22 cm/hr with a large coefficient of variation of 1.95. The geometric mean of the combined data was close to the value at French Regional Park, and it is expected that the soil in this area is compacted and may also benefit from soil remediation.

Soil remediation was performed in Fall 2008 on the treatment plots. In Summer 2009, 30 follow-up measurements of Ksat were taken on each plot type (See Figure 7.1.6). These measurements revealed that there was less variability in Ksat values than the previous year within each plot, but between plots there was significant variability. The post-remediation results are summarized in Table 7.1.6.

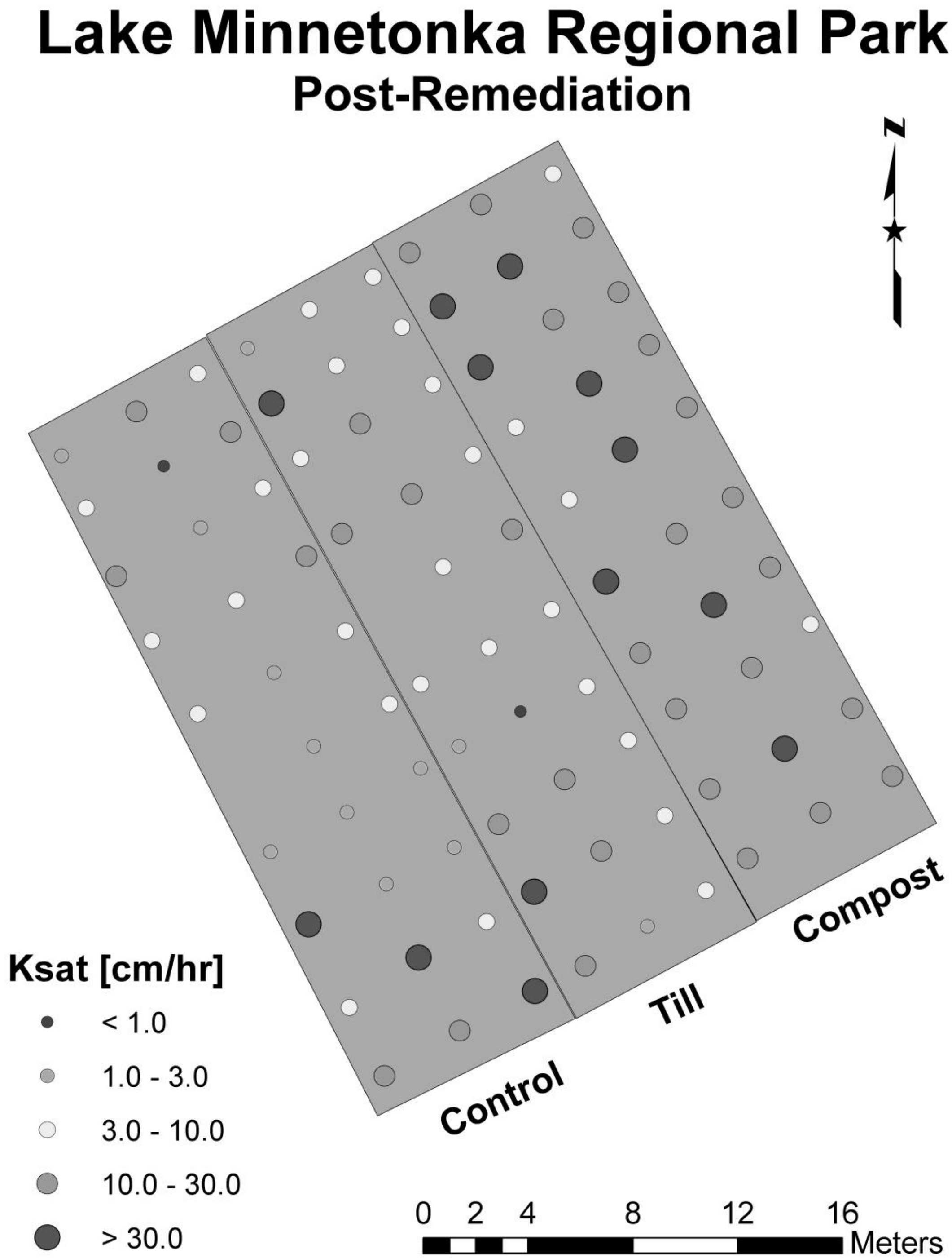

Figure 7.1.6 The spatial variability of Ksat at Lake Minnetonka Regional Park (post-remediation).

Table 7.1.6 Lake Minnetonka Regional Park: year two results.

	Lake Minnetonka Regional Park Year Two		
Plot:	Control	Till	Compost
# Measurements	29	29	30
Average [cm/hr]	13.27	10.80	23.72
St. Dev [cm/hr]	19.86	11.43	18.43
COV	1.50	1.06	0.78
Geomean [cm/hr]	6.12	7.10	18.24

Testing revealed that the geometric mean of the control plot was 1.90 times the values of the control area from the previous year. However, using the t-test methods outlined in Chapter Six, the statistical difference in means was not significant at a 0.01 significance level; therefore they may be treated as equal. The geometric mean of the till plot was 1.2 times that of the control plot, but was not statistically different from the control plot mean ($P \approx 0.3$). The tillage treatment did not have a substantial effect on improving the infiltration capacity of the soil. The compost plot had the highest geometric mean (Ksat = 18.24 cm/hr) and was statistically different from the control area ($P << 0.01$). Its geometric mean was 3.0 times that of the control plot. The f-test results show that the till and compost plots were also significantly less variable than the pre-remediation control area ($P = 0.007$ and $P < 0.001$, respectively).

From this it is concluded that the compost was effective in improving the infiltration capacity of the soil, but deep tillage alone was ineffective. There were inter-annual changes in the geometric mean of Ksat on the control plot, but means between years were not statistically different at the 0.01 significance level used. A third year assessment was not chosen for this site.

7.1.3 Maple Lakes Park

Maple Lakes Park was the last site to be evaluated during the first year of the study. Figure 7.1.7 shows that the soil Ksat in Maple Lakes Park was more spatially uniform than Lake Minnetonka or French Regional Park. Most measurements were between 1.0 and 3.0 cm/hr. There was no interference from trees or any other obstacles, so the whole initial assessment area was used for post-remediation testing. Ksat values in pre-remediation plot areas are summarized in Table 7.1.7.

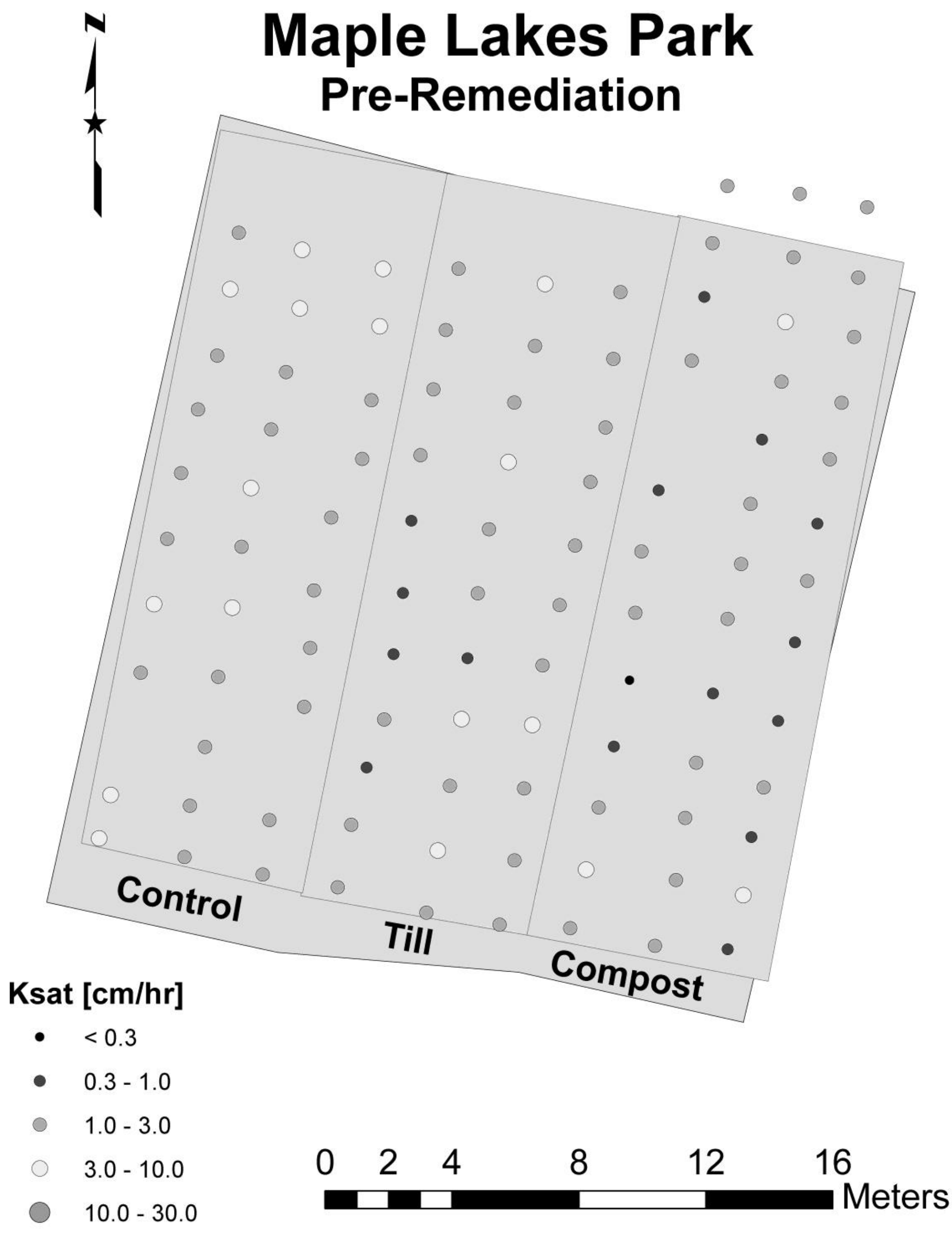

Figure 7.1.7 The spatial variability of Ksat at Maple Lakes Park (pre-remediation).

Table 7.1.7 Maple Lakes Park: year one results.

	Maple Lakes Park Year One, Pre-Remediation		
Plot:	Control	Till	Compost
# Measurements	31	33	35
Average [cm/hr]	3.09	2.32	1.47
St. Dev [cm/hr]	1.74	1.80	0.86
COV	0.56	0.78	0.59
Geomean [cm/hr]	2.72	1.91	1.25

The pre-remediation testing shows that the geometric means were lower than the previous two sites (1.25 to 2.72 cm/hr), but were within the same order of magnitude. The coefficients of variations were lower at Maple Lakes Park than the other two sites tested. This site may also benefit from the use of soil amendments. As discussed in Chapter Six, the different plots types have statistically different means from one another, so post-remediation values will be compared between respective plots and not a larger control area like the previous two sites.

Figure 7.1.8 shows Maple Lakes Park after soil remediation had been performed. The control plot does not appear to be as uniform as the previous year. The till and compost plots show more locations with larger Ksat values than previously observed. No values below 3.0 cm/hr appear on the compost plot. The post-remediation results during the second year of testing are summarized in Table 7.1.8.

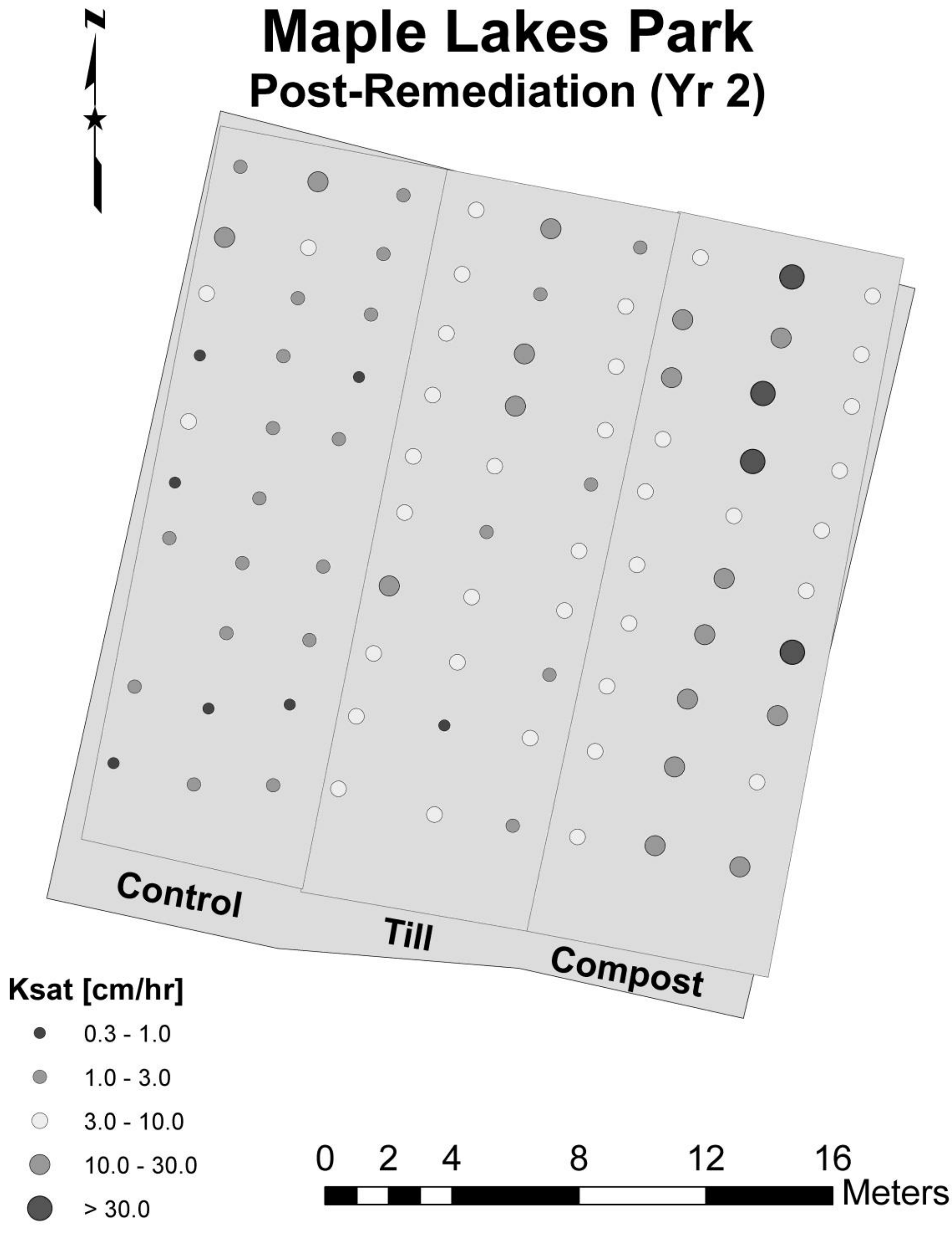

Figure 7.1.8 The spatial variability of Ksat at Maple Lakes Park (year two, post-remediation).

Table 7.1.8 Maple Lakes Park: year two results.

	Maple Lakes Park Year Two		
Plot:	Control	Till	Compost
# Measurements	28	30	30
Average [cm/hr]	3.17	5.60	14.80
St. Dev [cm/hr]	4.97	3.74	12.91
COV	1.57	0.67	0.87
Geomean [cm/hr]	1.94	4.43	11.15

During the second year of testing the control plot was lower than the initial assessment. The geometric mean dropped from 2.72 cm/hr to 1.94 cm/hr. The mean, however, was statistically the same ($P \approx 0.04$), indicating that the control did not change significantly. The mean of the till plot was 2.3 times that of the control plot in year two. The compost plot had the highest geometric mean, 11.15 cm/hr. Its geometric mean was 5.7 times the control plot. The f-test results show that the till and compost plots were statistically similar to the pre-remediation till and compost plots ($P = 0.25$ and $P = 0.27$, respectively).

Unlike the previous two sites, the deep tillage treatment proved to be effective at improving the permeability of the soil. The compost plot was the most effective at improving the infiltration capacity of the soil. A third year assessment was performed to determine if the compost would still be viable the next year. Figure 7.1.9 shows the results of testing during the spring of the third year. Large variability can be seen in the till and compost plots from the previous year. There are fewer locations with high permeability (> 10 cm/hr). The third year testing results are summarized in Table 7.1.9.

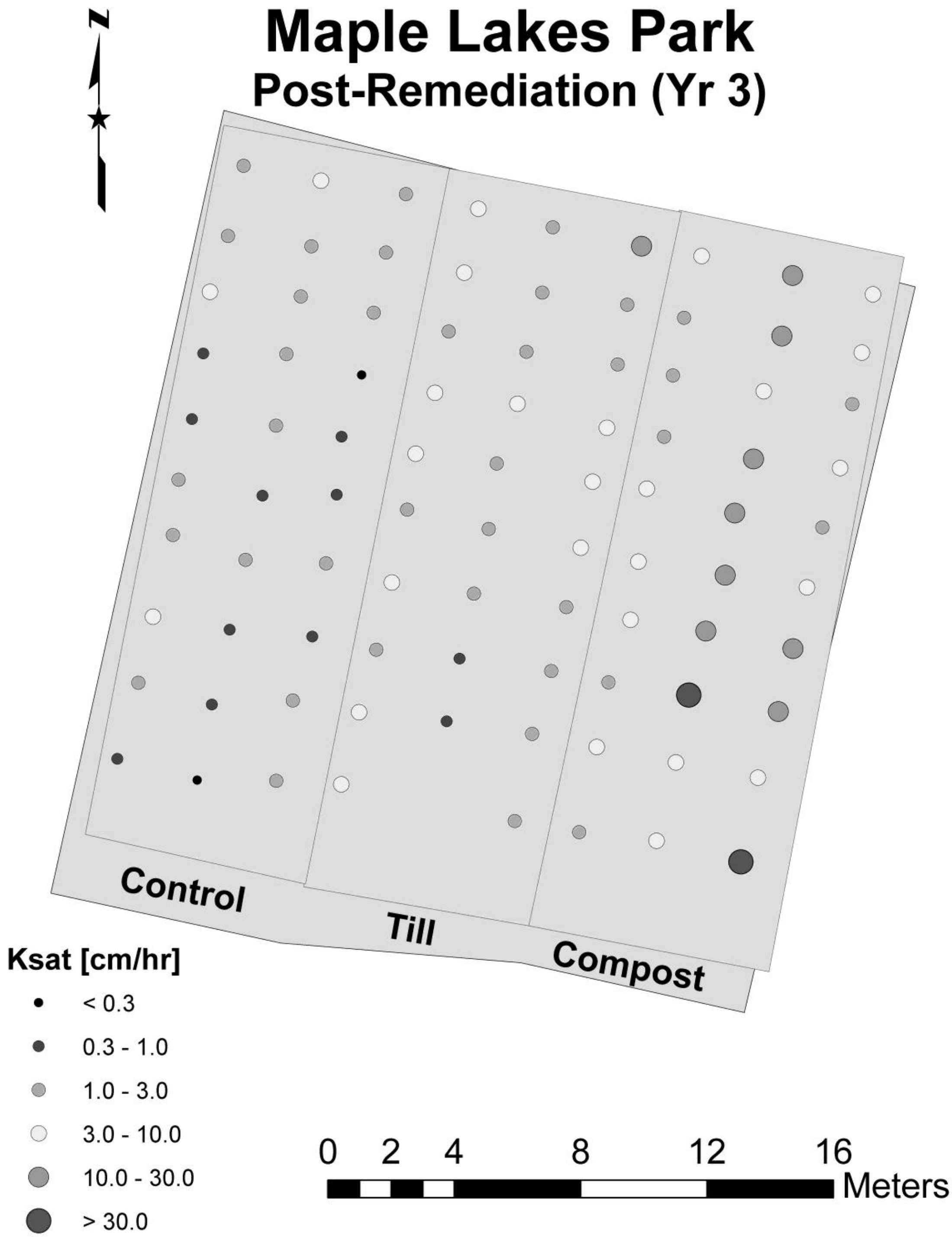

Figure 7.1.9 The spatial variability of Ksat at Maple Lakes Park (year three, post-remediation).

Table 7.1.9 Maple Lakes Park: year three results.

	Maple Lakes Park Year Three		
Plot:	Control	Till	Compost
# Measurements	30	29	30
Average [cm/hr]	1.66	3.24	10.19
St. Dev [cm/hr]	1.64	2.89	10.95
COV	0.99	0.89	1.07
Geomean [cm/hr]	1.21	2.49	6.65

The geometric mean of each plot was lower by approximately the same ratio: three-fifths. This may be due to seasonal effects like those observed at French Regional Park. When compared to the values observed in the control plot, the geometric mean of Ksat in the till plot was 2.1 times those observed in the control plot. The geometric mean of compost plot was 5.5 times that of the control plot value. This compares to the year two ratios of 2.3 and 5.7 for the till-to-control and compost-to-control ratios.

The Maple Lakes Park soils were the most consistent in the improvements over the Ksat of the control plot. The compost proved to still be viable a year-and-a-half after the remediation was performed.

7.1.4 Summary of Ksat Results

The ratio of the geometric means of Ksat between the treated plots and the control plot are summarized in Table 7.1.10 for each site. This ratio is used to determine the effectiveness of each remediation technique.

Table 7.1.10 The effectiveness of remediation techniques summary table.

Study Site	Assessment Period	Ratio of the Geometric Mean of Ksat: Till Plot / Control Plot	Ratio of the Geometric Mean of Ksat: Compost Plot / Control Plot
French Regional Park:	Year Two (Summer 2009)	0.6*	1.5*
	Year Three (Spring 2010)	0.5	1.2*
	Year Three (Summer 2010)	N/A	2.7
Lake Minnetonka Regional Park:	Year Two (Summer 2009)	1.2*	3
Maple Lakes Park:	Year Two (Summer 2009)	2.3	5.7
	Year Three (Spring 2010)	2.1	5.5

* indicates the means of the compared plots are not statistically different from one another

Soil remediation was least effective at French Regional Park. Tilling reduced the infiltration capacity of the soil. Compost addition was only effective at improving the infiltration capacity of the soil during the summer of 2010. The till plot's mean Ksat at Lake Minnetonka Regional Park was not statistically different from the control plot's mean and was not considered an effective treatment. The compost plot had a geometric mean that was three times the geometric mean of the control plot. The soil remediation techniques at Maples Lakes Park were the most effective at improving the infiltration capacity of the soil. The till plot's geometric means of Ksat were 2.1 to 2.3 times that of the control plot. The compost plot's geometric means of Ksat were 5.5 to 5.7 times that of the control plot. Maples Lake Park shows the most consistency in effectiveness between years.

The results of the f-tests showed that French Regional Park and Lake Minnetonka Regional Park soils were significantly more variable pre-remediation than post-remediation when comparing control area values to the treated plots. Maple Lakes Park had a low variability in Ksat. The pre-remediation and post-remediation standard deviations were statistically similar for the till and compost plots. These results were predicted by the hypothesis that highly variable soils have more connected pathways and tilling in these soils may negatively affect saturated hydraulic conductivity.

7.2 Green-Ampt Modeling of Ksat

Different scenarios using a Green-Ampt model were created using different design storms, moisture conditions, and intensity factors (See Appendix B for methods). The model used the saturated hydraulic conductivity values found for each plot type during the second year of the study at Maple Lakes Park. The results for the different scenarios are in Table 7.2.1.

Table 7.2.1 The portion of precipitation that resulted in runoff for Green-Ampt model. Applied to plots in Maple Lake Park, Maple Grove, Minnesota.

Design Storm:	Precipitation [cm]	Δθ	Intensity Factor	Portion of Precipitation that Results in Runoff (%)		
				Control Plot	Till Plot	Compost Plot
2 yr, 1 hr	3.18	0.1	1	13.3	0.0	0.0
2 yr, 1 hr	3.18	0.1	2	88.9	38.3	3.0
2 yr, 1 hr	3.18	0.3	1	0.0	0.0	0.0
2 yr, 1 hr	3.18	0.3	2	51.8	4.0	0.0
10 yr, 1 hr	4.39	0.1	1	28.4	3.3	0.0
10 yr, 1 hr	4.39	0.1	2	113.4	66.5	19.2
10 yr, 1 hr	4.39	0.3	1	7.8	0.0	0.0
10 yr, 1 hr	4.39	0.3	2	82.2	32.0	2.1
25 yr, 1 hr	5.18	0.1	1	36.1	9.3	0.0
25 yr, 1 hr	5.18	0.1	2	125.3	81.0	32.5
25 yr, 1 hr	5.18	0.3	1	15.9	0.0	0.0
25 yr, 1 hr	5.18	0.3	2	95.5	47.3	7.6
100 yr, 1 hr	6.53	0.1	1	45.5	20.4	2.0
100 yr, 1 hr	6.53	0.1	2	139.5	98.0	52.5
100 yr, 1 hr	6.53	0.3	1	27.3	2.4	0.0
100 yr, 1 hr	6.53	0.3	2	114.8	69.5	25.4

The results show that the control plot led to higher percentages of runoff from the rainfall than the till or compost plot. In four cases, the one-hour event with an intensity factor of two, the control plot could not accommodate all of the runoff from the connected impervious area. This resulted in 113.4% to 139.5% of runoff from the precipitation. The average percent of runoff from all of these scenarios for the control, till, and compost plots were 61.6%, 29.5%, and 9.1% respectively. The runoff generated by the compost plot was ~1/6 that of the runoff in the control plot and ~1/3 of the runoff in the till plot. These results show that soil remediation can effectively reduce the amount of runoff from short, high intensity storms.

7.3 Soil Texture Analysis

The Research Analytical Lab (RAL) at the University of Minnesota performed hydrometer tests on nine samples gathered from soil cores taken at each site. Table 7.3.1 provides the % sand, silt, and clay of each sample as well as the associated texture class. The results show that the soil textures were not different between sites. Most of the soil samples were designated as a sandy clay loam texture. One sample at each site was designated as a sandy loam. Figure 7.3.1 shows the values from Table 7.3.1 plotted on a texture triangle. Most of the samples are near the borders of sandy clay loam, loam, and sandy loam.

Table 7.3.1 Soil texture analysis results.

Soil Texture Analysis

Sample Name	Sand (%)	Silt (%)	Clay (%)	Soil Texture
FR - Control	58.5	24.5	17	Sandy Clay Loam
FR – Till	59.5	24.8	15.8	Sandy Loam
FR - Compost	53.5	24.5	22	Sandy Clay Loam
LM - Control	54.5	25.8	19.8	Sandy Loam
LM – Till	57	22.5	20.5	Sandy Clay Loam
LM - Compost	54.8	25	20.3	Sandy Clay Loam
MP - Control	52.3	26.5	21.3	Sandy Clay Loam
MP – Till	49.8	27.3	23.0	Sandy Clay Loam
MP - Compost	71.5	13.0	15.5	Sandy Loam

French Regional Park (FR), Lake Minnetonka Regional Park (LM), and Maple Lakes Park (MP).

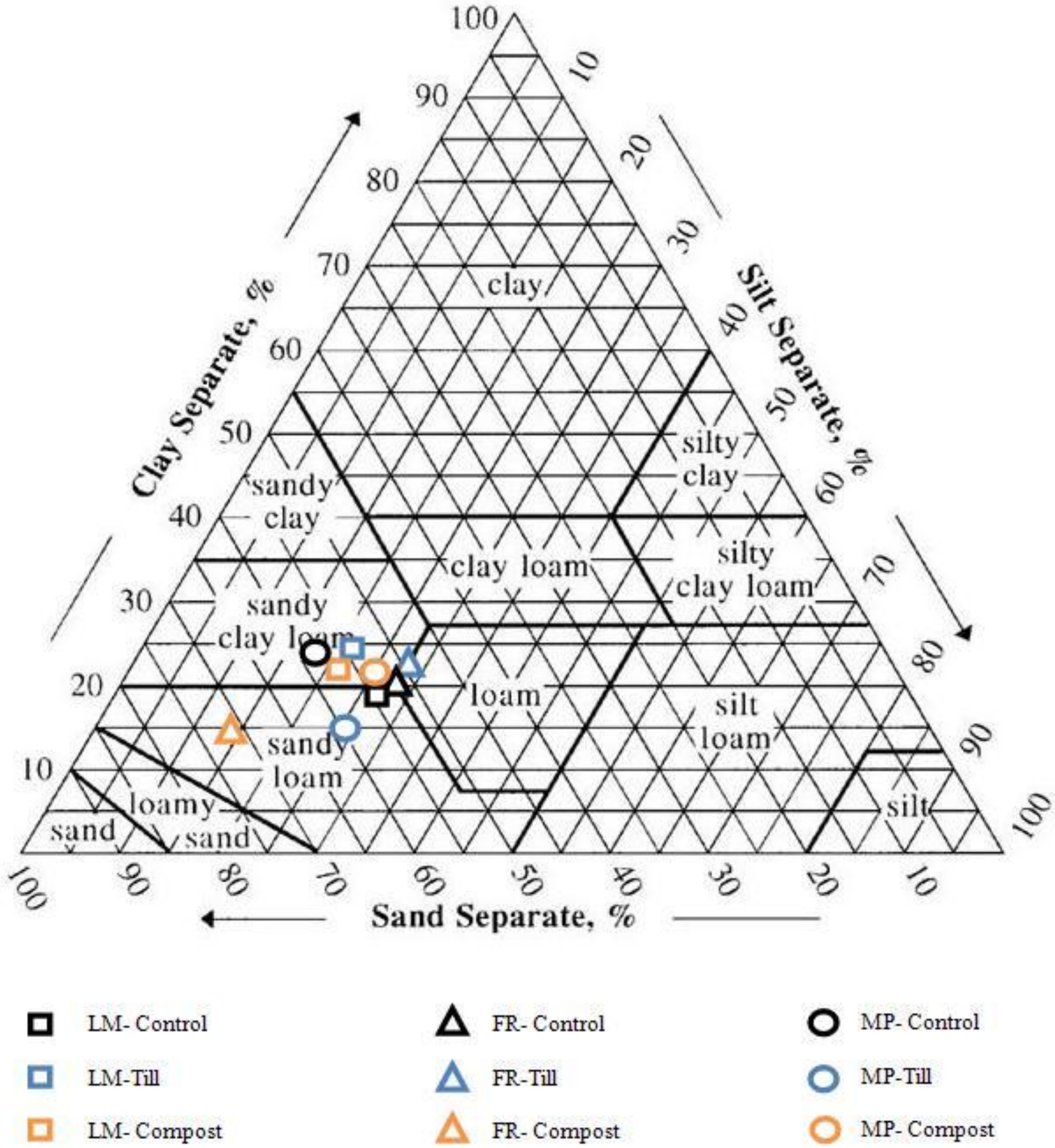

Figure 7.3.1 The plotted results of Table 7.3.1. This figure was modified from the original NRCS Soil Texture Calculator output (NRCS, 2010).

The results of the texture analysis show that each site did not differ greatly in soil texture in the 0” to 12” depth range. One of the criteria of the site selection process was to find sites with different soil textures to compare the effectiveness of remediation. This criterion was not met based on the findings of the RAL. The soil texture may vary between sites below the 12" depth, but samples were not analyzed below this depth.

Saxton and Rawls (2006) estimated that a sandy loam should have a saturated hydraulic conductivity of 5.03 cm /hr and sand clay loam 1.13 cm/hr. The geometric mean values of plots during the second year of the study (when the soil coring took place) were between 1.94 cm/hr and 18.24 cm/hr. The values predicted by Saxton and Rawls (2006) are within an order of magnitude of the values found by this study. Their estimates differed the most from the compost plot, but this is not unexpected since their estimates were for soils with only 2.5% organic matter. The organic matter content was much higher in the compost plot.

7.4 Soil Bulk Density

The bulk density of the soil was measured over the entire assessment area for each site during the first year of this study. The bulk density measurements were made near the locations of the Modified Philip-Dunne Infiltrometer tests to determine if there was a relationship between saturated hydraulic conductivity and bulk density. Second year measurements were conducted on the respective plots for each site. These measurements were not taken near measurements of saturated hydraulic conductivity. Measurements were compared with the Natural Resources Conservation Service's Soil Test Kit Guide, which provides a table relating bulk density with root growth ability (See Table 7.4.1). Bulk density measurements were compared to the root growth ability because plant growth can affect the saturated conductivity of the soil. Bulk density measurements will be compared to sandy clay loam because the results of the soil textural analysis showed that this soil texture was the most common. For this soil a bulk density less than 1.40 g/cm^3 is ideal for root growth. Bulk densities near 1.60 g/cm^3 may restrict root growth. Finally, bulk densities above 1.75 g/cm^3 would restrict root growth.

Table 7.4.1 The relationship between soil bulk density and root growth ability. Table was re-created from The Soil Test Kit Guide (NRCS Soil Quality Institute, 1999).

Soil Texture	Ideal Bulk Densities [g/cm^3]	Bulk Densities that may affect root growth [g/cm^3]	Bulk Densities that restrict root growth [g/cm^3]
sands, loamy sands	< 1.60	1.69	>1.80
sandy loams, loams	<1.40	1.63	>1.80
sandy clay loams, loams, clay loams	<1.40	1.60	>1.75
silts, silt loams	<1.30	1.60	>1.75
silt loams, silty clay loams	<1.40	1.55	>1.65
sandy clays, silty clays, some clay loams (35-45% clay)	<1.10	1.49	>1.58
clays (> 45% clay)	<1.10	1.39	>1.47

7.4.1 Clifton E. French Regional Park

French Regional Park had an average bulk density of 1.41 g/cm^3 during the first year, which is near the level indicated for ideal growth conditions. Only one measurement was greater than 1.60 g/cm^3, which may affect root growth. Figure 7.4.1 plots the saturated hydraulic conductivity (Ksat) values versus the bulk density measurements taken at a particular location on the site. The figure is a scatter plot that shows no correlation between the two measurement types. This indicates that, at this site, Ksat cannot be related to bulk density measurements. Table 7.4.2 summarizes the measurements taken during the first and second year of the study at French Regional Park.

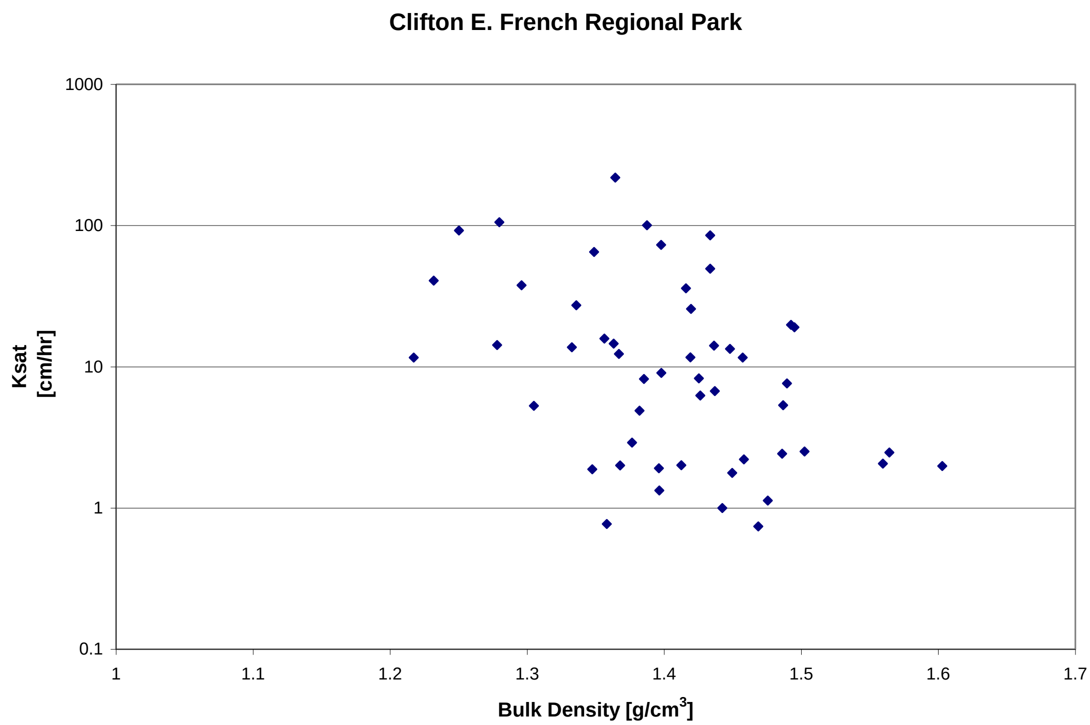

Figure 7.4.1 Ksat vs. bulk density at Clifton E. French Regional Park.

Table 7.4.2 Bulk density measurements at Clifton E. French Regional Park.

Clifton E. French Regional Park

	Year One	**Year Two**		
	Pre-Remediation (Entire Site)	Control	Till	Compost
# Measurements	56	9	9	9
Average [g/cm^3]	1.41	1.44	1.42	1.15
St. Dev [g/cm^3]	0.08	0.07	0.17	0.13
COV	0.06	0.05	0.12	0.11

Bulk density averages on the control and till plot were similar to the average bulk density of the site from the previous year. Only the compost plot showed a reduction in bulk density. Its average bulk density was 1.15 g/cm^3, which was similar to the bulk density recorded for compost at Lake Minnetonka Regional Park. This value was 18% lower than the pre-remediation site average and 20% lower than the control plot. All but one of the bulk density measurements on the compost plot was less than 1.40 g/cm^3.

7.4.2 Lake Minnetonka Regional Park

Lake Minnetonka Regional Park had the highest bulk density of the three sites assessed during the first year of the study. Eight of the sixty-six measurements had a value of 1.60 g/cm^3 or over. This value would indicate a bulk density that may affect root growth according to Table 7.4.1. The highest measurement recorded was 1.72 g/cm^3, which may affect root growth. Figure 7.4.2 plots the saturated hydraulic conductivity (Ksat) values versus the bulk density measurements taken at a particular location on the site. The figure is a scatter plot that shows no correlation between the two measurement types. Again no relationship was found between Ksat and soil bulk density at this site. Table 7.4.3 summarizes the measurements taken during the first and second year of the study.

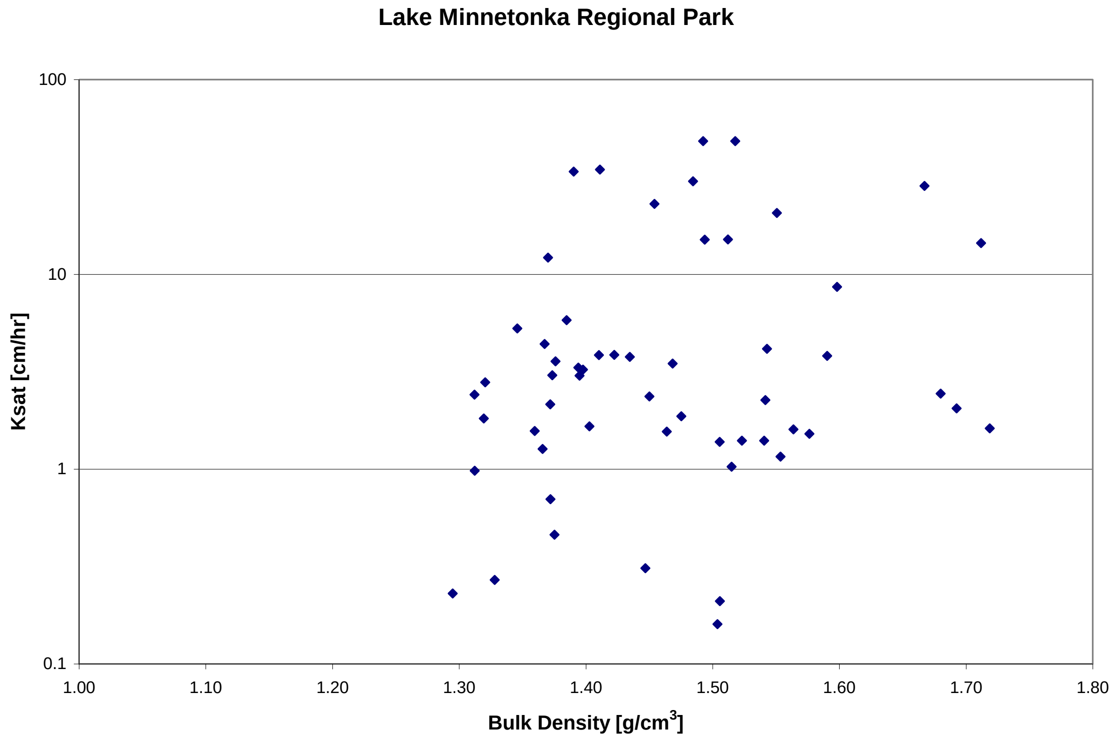

Figure 7.4.2 Ksat vs. bulk density at Lake Minnetonka Regional Park.

Table 7.4.3 Bulk density measurements at Lake Minnetonka Regional Park.

Lake Minnetonka Regional Park	Year One	Year Two		
	Pre-Remediation (Entire Site)	Control	Till	Compost
# Measurements	66	9	9	9
Average [g/cm^3]	1.47	1.59	1.46	1.14
St. Dev [g/cm^3]	0.11	0.10	0.08	0.08
COV	0.07	0.07	0.05	0.07

The bulk density measurements taken in year two show that the control plot had a higher average than the previous year. Five of the nine measurements were over 1.60 g/cm^3 with one measurement over 1.75 g/cm^3, indicating that bulk density may affect root growth. Tilling did not improve the bulk density of the soil. Its average was similar to the previous year. The average bulk density on the compost plot was 1.14 g/cm3. This value was 22% lower than the site average from the year before, and 28% lower than the control in the same year.   All of the bulk density measurements were less than 1.40 g/cm^3, which is ideal for root growth (See Table 7.4.1).

7.4.3 Maple Lakes Park

The results of bulk density testing at Maple Lakes Park were similar to French Regional Park. Maple Lakes Park had an average bulk density of 1.39 g/cm^3during the first year, which is near the level indicated for ideal growth conditions. No measurements were greater than 1.60 g/cm^3, and most were below 1.40 g/cm^3. Figure 7.4.3 plots the saturated hydraulic conductivity (Ksat) values versus the bulk density measurements taken at a particular location on the site. The figure is also a scatter plot that shows no correlation between the two measurement types. Table 7.4.4 summarizes the measurements taken during the first and second year of the study at Maple Lakes Park

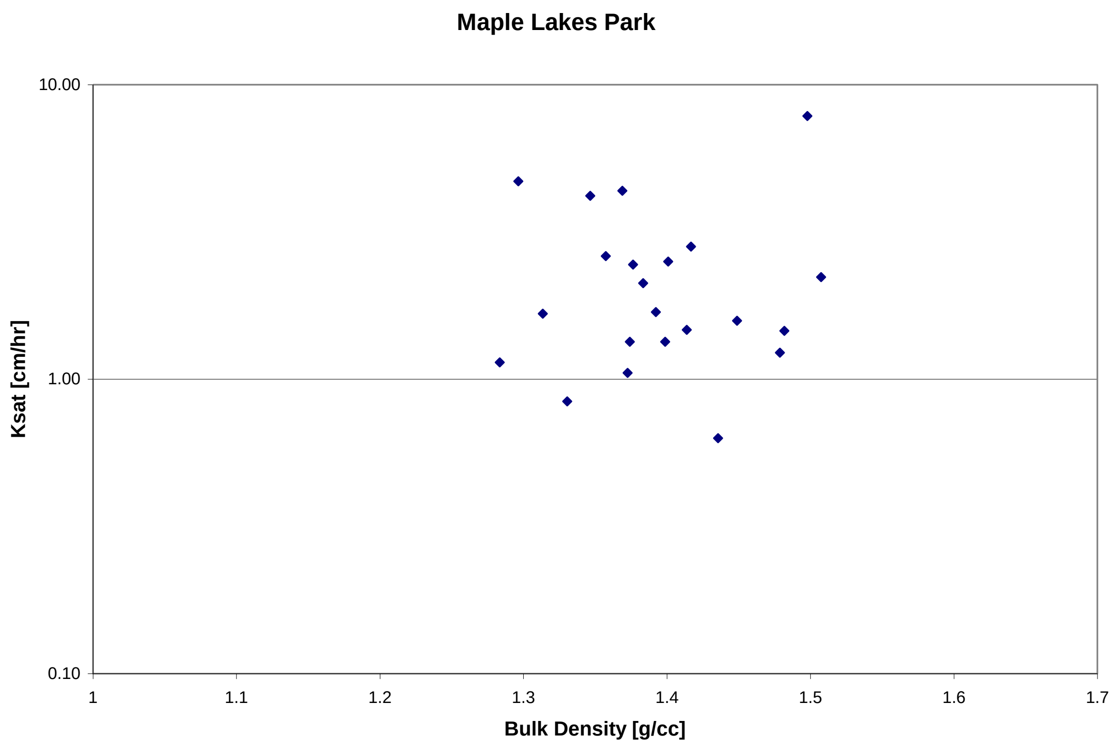

Figure 7.4.3 Ksat vs. bulk density at Maple Lakes Park.

Table 7.4.4 Bulk density measurements at Maple Lakes Park.

Maple Lakes Park	Year One	Year Two		
	Pre-Remediation (Entire Site)	Control	Till	Compost
# Measurements	22	6	6	6
Average [g/cm^3]	1.39	1.48	1.33	0.93
St. Dev [g/cm^3]	0.06	0.07	0.04	0.09
COV	0.04	0.04	0.03	0.10

The control increased in bulk density by approximately 6.5% from the previous year's average. However, no bulk densities were expected to affect root growth. The average bulk density on the till plot was approximately 4% less than the previous year's average. Only the compost plot showed a significant reduction in bulk density. Its average bulk density was 0.93 g/cm^3, which was the lowest average bulk density of any site. This value was 33% lower than the site average and 37% lower than the control plot. The highest bulk density measured on the compost plot was only 1.05 g/cm^3.

There were similar results from the bulk density testing at all three sites. First, none of the saturated hydraulic conductivity measurements could be related to the bulk density measurements. This indicates that bulk density should not be used a surrogate measurement for determining the infiltration capacity of a soil. Second, there was no significant reduction in bulk density from the deep tillage treatment at any site. Lastly, compost addition is effective at reducing the bulk density of the surface layer of soil. This is not unexpected since organic matter in compost is less dense than the mineral matter found in soil. Reductions in average bulk density were between 18% and 37%.

7.5 Soil Strength

Soil strength measurements were obtained from a hand-held penetrometer. They were taken during Spring 2009 following soil remediation performed the previous fall. These measurements are compared with the findings of Taylor et al. (1966) who measured the root penetration percentages for different soil strengths, and found that cotton taproots penetration percentages decreased as the soil strength reached 2.5 MPa. Soil strengths greater than 2.5 MPa prevented root penetration.

For this study, nine penetrometer measurement locations on each plot were also compared with geometric mean of nearby measurements of saturated hydraulic conductivity (Ksat). Soil strength measurements from the 6” to 12” depth range are plotted versus the geometric means of Ksat to determine if a relationship can be found.

7.5.1 Clifton E. French Regional Park

The soil strength measurements for Clifton E. French Regional Park are shown in Figure 7.5.1.

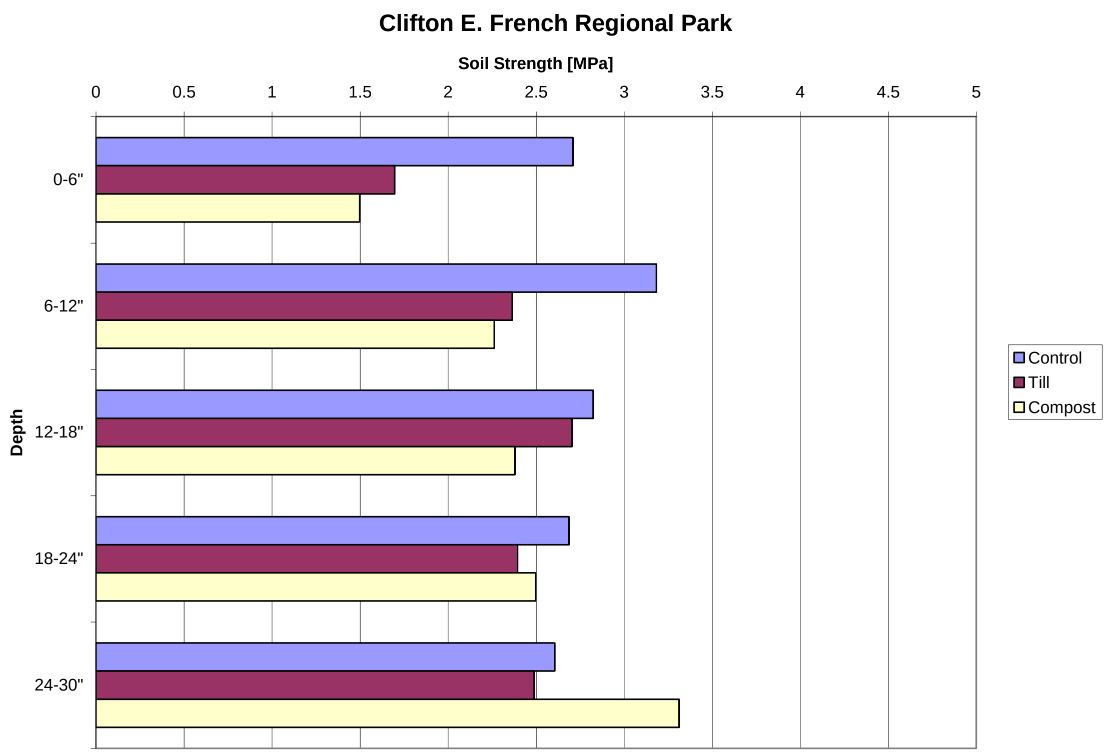

Figure 7.5.1 Penetrometer results at Clifton E. French Regional Park.

In the first six inches, the control plot had an average soil strength of 2.71 MPa, which was 1.6 to 1.8 times the soil strength average on the remediated plots. The soil strength on the control plot was higher than the treated plots up to 24 inches in depth. This is the maximum depth the subsoiler could remediate. The maximum soil strength on the control plot was 3.18 MPa, which is above the 2.5 MPa level specified by Taylor et al. (1966) that affects root growth. Below six inches in depth, the treatment plots' soil strength may affect root growth. The penetrometer measurements on the till and compost plots are comparable to each other, suggesting that the deep tillage performed on each plot was the main cause of the strength reduction. No additional reduction in soil strength was obtained from the compost addition.

Figure 7.5.2 shows the soil strength plotted versus the geometric mean of Ksat values at nine locations on each plot. There is no observable trend that shows Ksat being affected by the soil strength at this site. The control plot had higher values of soil strength, but a very wide range of Ksat values. The till and compost had a similar range of soil strength to each other, but had values that were typically lower than the control plot. No trend relative to soil strength could be observed in saturated hydraulic conductivity.

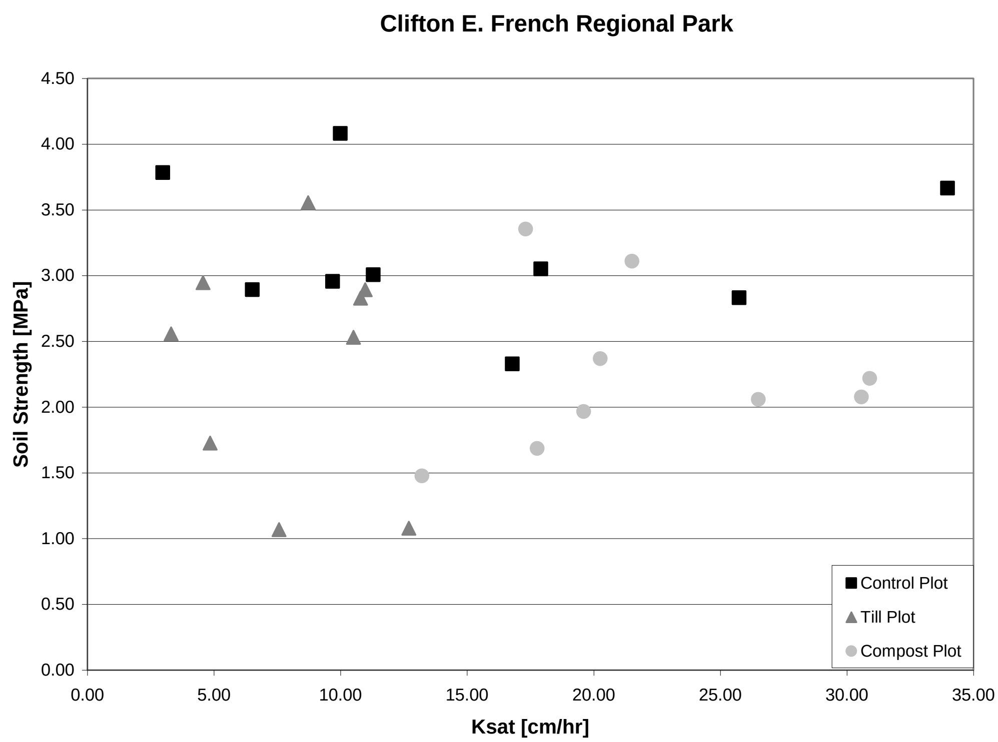

Figure 7.5.2 Soil strength vs. Ksat at Clifton E. French Regional Park.

7.5.2 Lake Minnetonka Regional Park

The soil strength measurements for Lake Minnetonka Regional Park are shown in Figure 7.5.3. The control plot at Lake Minnetonka Regional Park was too hard for the penetrometer be pushed into the soil without bending the device's rod. Thus, no measurements were obtained for the control plot for comparison. The soil strength measurements on the till and compost plot were comparable to each other except in the 6 to 12 inch depth range as it neared the 2.5 MPa level. The compost plot may begin to affect root growth starting in this depth range, but it expected that the till plot would not be affected until below 12 inches in depth.

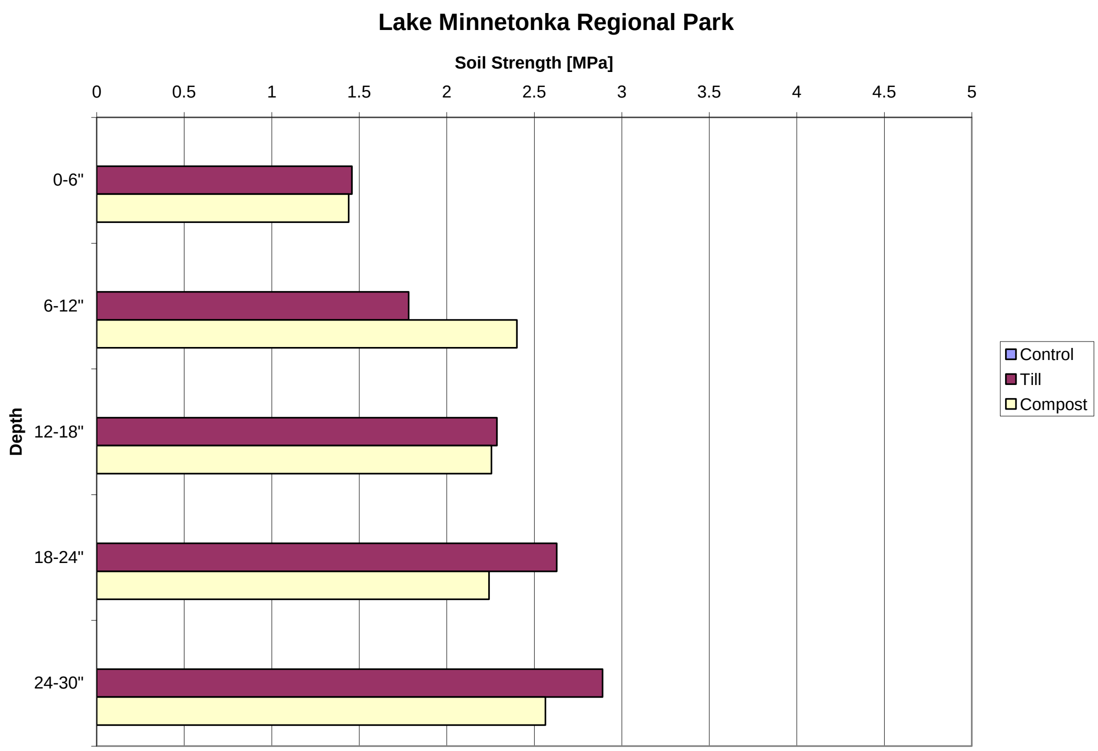

Figure 7.5.3 Penetrometer results at Lake Minnetonka Regional Park.

Figure 7.5.4 shows the soil strength plotted versus the geometric mean of Ksat values at nine locations on each plot. The till plot had a narrow range of Ksat, but a wide range of soil strength. This differed from the compost plot, which had a wider range of Ksat, but a narrower range of soil strength. However, there is no observable trend that shows Ksat being affected by the soil strength.

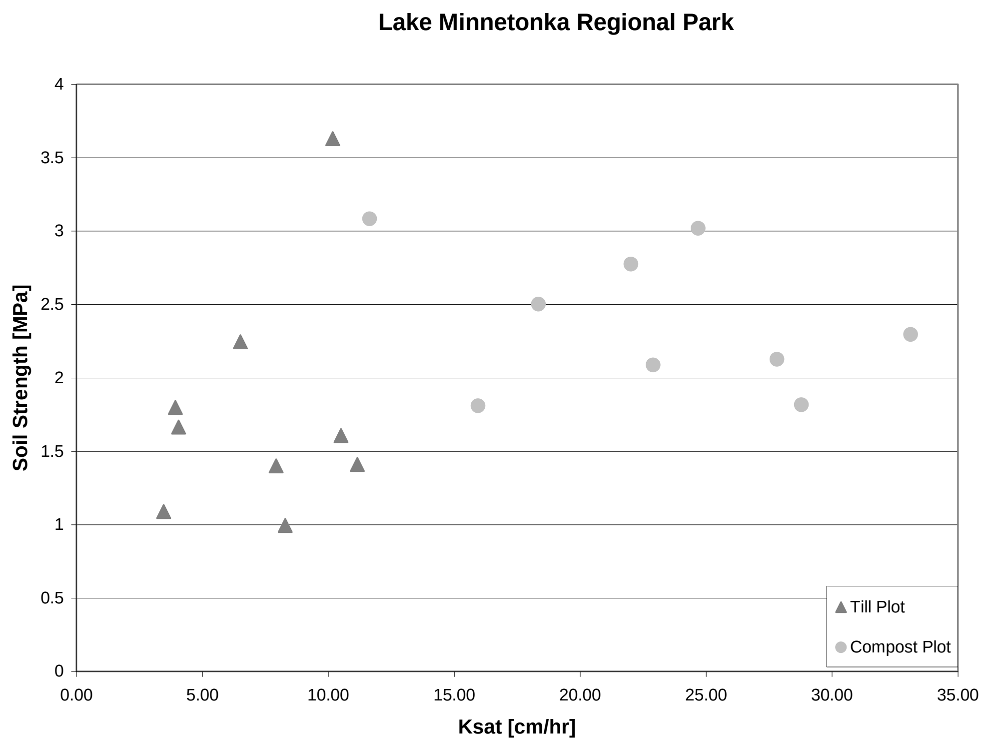

Figure 7.5.4 Soil strength vs. Ksat at Lake Minnetonka Regional Park.

7.5.3 Maple Lakes Park

The soil strength measurements for Maple Lakes Park are shown in Figure 7.5.5. Maple Lakes Park had a higher soil strength in the control plot than French Regional Park. In the first six inches, the control plot had an average soil strength of 3.51 MPa, which was 2.0 to 2.4 times the soil strength average on the remediated plots. The soil strength on the control plot was higher than the treated plots up to 12 inches in depth. This was less than the maximum depth the subsoiler could remediate. The maximum soil strength on the control plot was 4.35 MPa, which is well above the 2.5 MPa level specified by Talor et al. (1966) that may affect root elongation. The high soil strength of the soil on the control plot is expected to affect root growth at all depths. Above six inches in depths, the treatment plots' soil strength may affect root growth. The penetrometer measurements on the till and compost plots were also comparable to each other, again suggesting that the deep tillage performed on each plot was the main cause of the strength reduction.

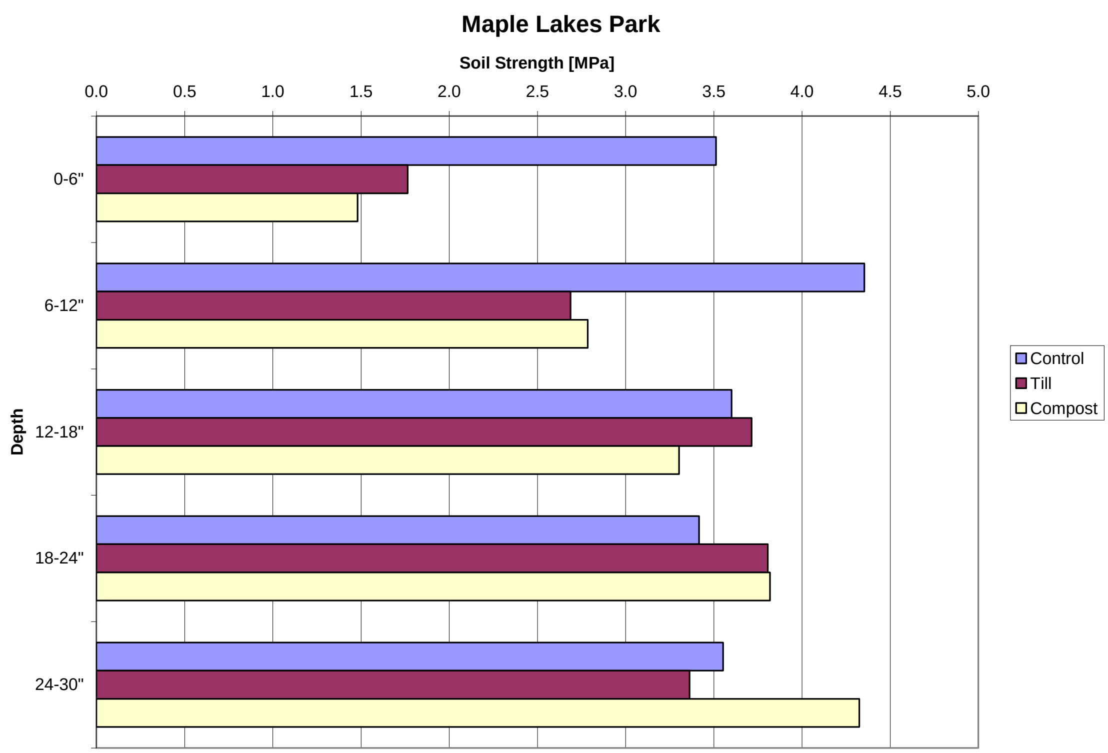

Figure 7.5.5 Penetrometer results at Maple Lakes Park.

Figure 7.5.6 shows the soil strength plotted versus the geometric mean of Ksat values at nine locations on each plot. The control and till plots had a similar range of Ksat values, but the till plot had a lower average of soil strength. The compost plot had higher Ksat values and low soil strengths. A slight trend may be observed from this plot, but it appears that compost addition was the main causes of increased Ksat, and not the subsoiling and spading operations, which performed the mechanical loosening.

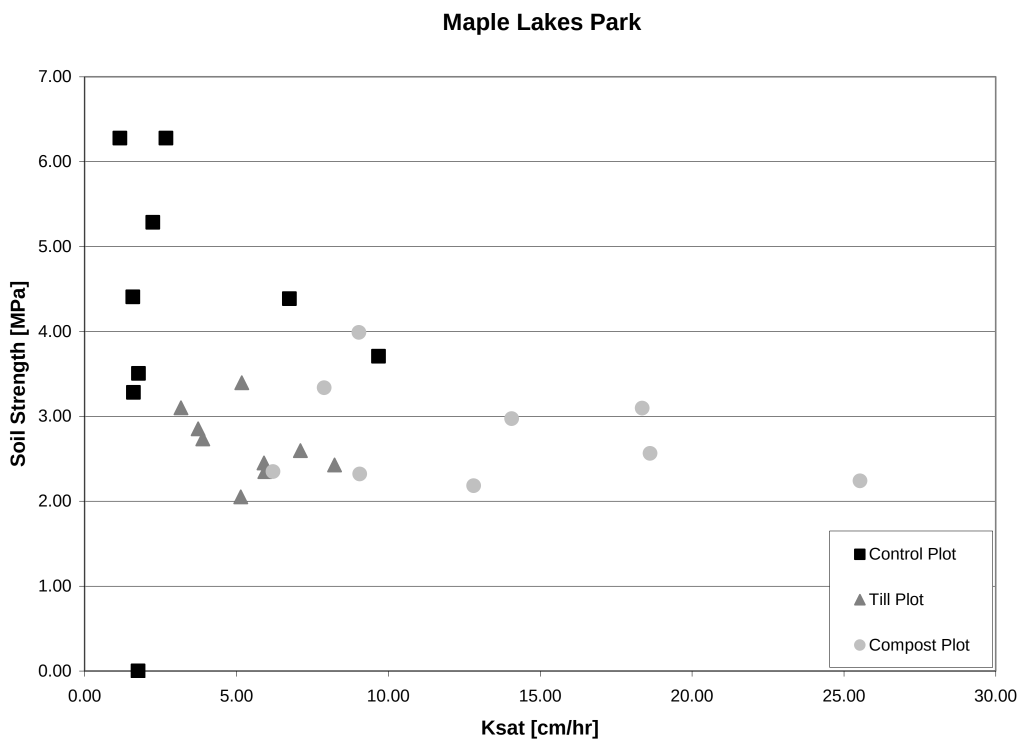

Figure 7.5.6 Soil strength vs. Ksat at Maple Lakes Park.

7.5.4 Soil Remediation Analysis

Soil remediation reduced the level of soil compaction. The remediated plots at each site had lower soil strengths than the control plots. This reduction was noticed up to 24 inches in depth, however root growth still may be affected in depths greater than 12 inches. Gregory et al. (2006) found that soil strength was negatively correlated with the surface infiltration rate, meaning that as soil strength increases the infiltration rate should decrease. The results presented here did not indicate a similar correlation. Chaplin et al. (2008) concluded that measurements of soil strength are not a good indicator for predicting the effectiveness of a tillage operation to improve infiltration. Finally, the addition of compost to the soil did not affect the strength of the soil. Compost and till plots had similar soil strength averages.

Chapter Eight

Summary and Conclusions

Measurements of saturated hydraulic conductivity (Ksat) and soil bulk density were made at three sites around the Minneapolis metropolitan area to assess the level of soil compaction during the summer of 2008. These sites were Clifton E. French Regional Park (Plymouth, MN), Lake Minnetonka Regional Park (Minnetrista, MN), and Maple Lakes Park (Maple Grove, MN). Each site was determined to be compact and may benefit from soil remediation. After the initial assessment soil remediation was performed in the fall of 2008. A subarea of each site was divided into three plots: a control plot and two treatment plots. The first treatment plot was deep-tilled with a subsoiler at 24 inches depth and was spaded to 12 inches depth. The second treatment plot was also deep-tilled, but three inches of compost was spread on the plot prior to spading. Follow-up measurements of Ksat were made in the spring of 2009 at each site to quantify the effectiveness of soil remediation. Bulk density and soil strength measurements were also used to assess the level of compaction on each plot and these measurements also were compared to measurements of Ksat. In the spring and summer of 2010, another round of Ksat measurements were taken to assess the seasonal effects on infiltration capacity, and to determine if the compost-treated plot was still effective.

8.1 Effectiveness of Soil Remediation

8.1.1 Tillage

Remediation by deep-tillage alone was ineffective at improving the infiltration capacity of the soil at Clifton E. French Regional Park and Lake Minnetonka Regional Park. At Clifton E. French Regional Park the mean Ksat of the till plot was not statistically different from the control plot during the second year of testing. During the spring testing in the third year of the study the mean Ksat value of the till plot was approximately half that of the control plot. Deep-tillage could have degraded the infiltration capacity of the soil, probably due to the disruption of macropores.

At Lake Minnetonka Regional Park, the mean value Ksat on the till plot was 1.2 times that of the control, but was not statistically different from the mean of the control plot. Deep-tillage by itself was effective in improving the infiltration capacity only at Maple Lakes Park, and provided consistent results. The geometric mean of Ksat in the till plot was 2.3 times that of the control plot during the second year of the study and 2.1 times during the third year. Remediation by deep-tillage alone at Clifton E. French Park and Lake Minnetonka Park did not effectively improve the capacity of the soil to infiltrate stormwater. Tilling operations may have damaged the structure of the soil and natural pathways created by fauna and flora, which could decrease the infiltration capacity of the soil. Meek et al. (1992), Schafer-Landefeld et al. (2004), and Spoor (2006) have all stated this as a consequence of tillage. Maple Lakes Park was a newly developed site. Its soil may not have had a well-developed network of connected pores as the previous two sites. If this is the case then tilling would not degrade the infiltration capacity of the soil as observed at the other two parks, but instead would improve it.

Tilling did not have a large effect on reducing the bulk density of the soil. The largest reduction in bulk density was 10% at Maple Lakes Park between the control plot and the till plot in the same year. The average reduction of bulk density was 4.9% (all till plots). Between the first and second year at Lake Minnetonka the bulk density of the till plot increased by 0.7%.

The average soil strength was lower on the till plots than the control plots; up to a maximum depth of 24 inches. The control plots had soil strengths in the first six inches of soil that were 1.6 to 2.0 times that of the till plots.

8.1.2 Compost Addition

Compost addition with deep tillage was the most effective soil remediation technique. The geometric means of Ksat on the compost plots were 2.7 to 5.7 times the geometric means of the control plots. The geometric means of Ksat were always higher on the compost plots than that of the control or till plots measured during the same time period.

The compost plot at each site showed the largest reductions in soil bulk density from the control plot. Compost addition reduced the bulk density of the soil by 18% to 37%. This was likely due to the large addition of organic matter, which has a smaller particle density than mineral matter.

The compost plots had similar reductions in soil strength. The average soil strength was lower on the compost plots than the control plots; up to a maximum depth of

24 inches. The control plots had soil strengths in the first six inches of soil that were 1.8 to 2.4 times that of the compost plots.

8.2 Assessment Techniques

Measurements of saturated hydraulic conductivity (Ksat) were compared with nearby measurements of soil bulk density and soil strength. No correlation between Ksat and bulk density was found. Meek et al. (1992) found a strong relationship between Ksat and bulk density using laboratory tests ($r^2 = 0.75$ for undisturbed cores, $r^2 = 0.83$ for columns using disturbed soil). This study's methods compared field measurements of Ksat and bulk density, which may have decreased the likelihood of finding a correlation. The results also showed that measurements of Ksat could not be related with measurements of soil strength. Gregory et al. (2006) found that field measurements of soil strength were negatively correlated with the surface infiltration rate between the depths of 10 and 20 cm (maximum Pearson correlation coefficient was -0.826). Gregory et al. (2006) suggested that measurements of soil strength to quickly indentify areas of compaction in lieu of the lengthy procedure of measuring infiltration rates.

Soil bulk density and soil strength measurements may be useful in identifying compact soils, but the findings of this research suggests that they were not useful in identifying the infiltration capacity of a soil. They should not be used as surrogates for determining the saturated hydraulic conductivity of a soil.

8.3 Implementation

Soil remediation is best performed in newly developed areas. There are a few reasons for this. First, deep-tillage may damage natural pathways in older developed areas. Natural pathways such as decaying roots, earthworm tunnels, and stable aggregates can improve the infiltration capacity of soil. If these pathways are destroyed, then the connected porosity decreases, which reduce the infiltration capacity. This consequence of deep-tillage was evident at French Regional Park. Second, sites in the process of being developed could see a lower cost of tilling with compost addition due to a larger scale operation than remediating already developed locations. Finally, there will be an increase in amendable area in new developments, because there will be less interference from trees and utility lines. Plot locations for this study had to factor in the locations of trees because the subsoiler had to operate outside of the crown of a tree to prevent damage to its roots.

8.4 Future Work

Follow-up studies are recommended for the compost plots to determine the longevity of the compost treatment. It is expected that over time the compost amendment will degrade and infiltration capacity could be affected. However, roots and soil fauna may become better established in soil with compost, causing the effectiveness of the compost on infiltration to extend for a longer time. Cogger (2005) reviewed several compost studies that suggest that compost treatments are still viable over five years after initial treatment.

Simulated stormwater run-off studies could also be used to determine the effectiveness of each plot to infiltrate stormwater. This project's proposal initially included plans to perform run-off testing, but materials were limited. Instead, Appendix B uses Ksat values from Maple Lakes Park to predict the run-off from different storm events.

Chapter Nine

References

Ahmed, Farzana. Personal Communication. 2010. St. Anthony Falls Laboratory, University of Minnesota, Minneapolis, Minnesota.

Ang, Alfredo H-S., and Wilson H. Tang. Probability Concepts in Engineering. Hoboken: John Wiley & Sons, Inc., 2007.

Asleson, B.C. 2007. The Development and Application of a Four-Level Rain Garden Assessment. M.S. Thesis. University of Minnesota, Minneapolis.

Asleson, B.C., R.S. Nestigen, J.S. Gulliver, R.M. Hozalski, and J.L. Nieber. The Development and Application of a Four-Level Rain Garden. SAFL Project Report 494, July 2007. <http://home.safl.umn.edu/bmackay/pub/pr/pr501.pdf>

A.S.T.M. D2216-05, 2005. Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM International, Ed.

A.S.T.M. D2937, 2010. Standard Test Method for Density of Soil in Place by the Drive Cylinder Method. ASTM International, Ed.

Bartens, Julia, et al. "Can Urban Tree Roots Improve Infiltration through Compacted Subsoils for Stormwater Management?" Journal of Environmental Quality 37.6 (2008): 2048-57.

Batey, T., and D.C. McKenzie. "Soil Compaction: Identification Directly in the Field." Soil Use and Management 22.2 (2006): 123-131.

Bauters, T. W. J., et al. "Physics of Water Repellent Soils." Journal of Hydrology 231-232(2000): 233-43.

Brander, K. E., K. E. Owen, and K. W. Potter. "Modeled Impacts of Development Type on Runoff Volume and Infiltration Performance." Journal of the American Water Resources Association 40.4 (2004): 961-9.

Chamberlain, Edwin J., and Anthony J. Gow. "Effect of Freezing and Thawing on the Permeability and Structure of Soils." Engineering Geology 13.1-4 (1979): 73-92.

Chaplin, Jonathan, Min Min, and Reid Pulley. 2008. "Compaction Remediation for Construction Sites." Final Report. Department of Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, Minnesota.

Chen, Y., et al. "Short-Term Tillage Effects on Soil Cone Index and Plant Development in a Poorly Drained, Heavy Clay Soil." Soil & Tillage Research 82.2 (2005): 161-71.

Cogger, C. "Potential Compost Benefits for Restoration of Soils Disturbed by Urban Development." Compost Science & Utilization 13.4 (2005): 243-251.

Craul, Phillip J. "Urban Soils: An Overview and Their Future". Reprinted from: "The Landscape Below Ground." Edited by G.W. Watson & D. Neely, 1994. International Society of Arboriculture, Savoy, IL.

Environmental Protection Agency (EPA). "Protection Water Quality from Urban Runoff." 2003. Retrieved July 16, 2008 from <http://www.epa.gov/npdes/pubs/nps_urban-facts_final.pdf>

Environmental Protection Agency (EPA). "Innovative Uses of Compost: Erosion Control, Turf Remediation, and Landscaping." Compost- New Applications For an Age-Old Technology. 1997. Received as a pamphlet.

Gee, G.W., and J.W. Bauder. "Particle-size Analysis." Methods of Soil Analysis Part 1 Physical and Mineralogical Methods. 2nd ed. Madison: American Society of Agronomy-Soil Science Society of America, 1986.

Gregory, J.H., et al. "Effect of urban soil compaction on infiltration rate." Journal of Soil and Water Conservation 61.3 (2006): 117-124.

Hamilton, G. W., and D. V. Waddington. "Infiltration Rates on Residential Lawns in Central Pennsylvania." Journal of Soil and Water Conservation 54.3 (1999): 564-568.

Harrison, Robert B., Henry, Charles L., and Dongsen Xue. 1998. "Field Test of Compost Amendment to Change Hydrology and Reduce Nutrient Runoff." Final Report. College of Forest Resources, University of Washington.

Henderson C., A. Levett, and D. Lisle. "The Effects of Soil Water Content and Bulk Density on the Compactibility and Soil Penetration Resistance of Some Western Australian Sandy Soils." Australian Journal of Soil Research 26 (1988): 391-400.

Huff, F.A. and J.R. Angel. 1992. "Rainfall Frequency Atlas of the Midwest." Midwestern Climate Center and Illinois State Water Survey. Bulletin 71. Champaign IL, 141p.

Jury, William A., and Robert Horton. Soil Physics. 6th ed. Hoboken: John Wiley & Sons, Inc., 2004.

Mays, Larry M. Water Resources Engineering. 2005 ed. Hoboken: John Wiley & Sons, Inc., 2005.

Meek, B. D., et al. "Infiltration-Rate of a Sandy Loam Soil - Effects of Traffic, Tillage, and Plant-Roots." Soil Science Society of America Journal 56.3 (1992): 908-13.

Modified Philip-Dunne Infiltrometer (MPD) Manual. 2010. St. Anthony Fall Laboratory, University of Minnesota, Minneapolis, Minnesota.

Moore, David S. and George P. McCabe. Introduction to the Practice of Statistics. 5th ed. New York: W.H. Freeman and Company, 2004.

Munoz-Carpena, Rafael, et al. "Field Evaluation of the New Philip-Dunne Permeameter for Measuring Saturated Hydraulic Conductivity." Soil Science 167.1 (2002): 9-24.

Nestingen, R. S. 2007. The Comparison of Infiltration Devices and Modification of the Philip-Dunne Permeameter for the Assessment of Rain Gardens. M.S. Thesis. University of Minnesota, Minneapolis.

NRCS Soil Texture Calculator. 2010. United States Department of Agriculture, National Resources Conservation Service. Accessed 18 August 2010 <http://soils.usda.gov/technical/aids/investigations/texture/>

NRCS Soil Quality Institute. 1999. Soil Quality Test Kit Guide. United States Department of Agriculture, Agriculture Research Service and National Resources Conservation Service. Kit guide can be obtained at <http://soils.usda.gov/sqi>

Ocean County Soil Conservation District (OCSCD), Schnabel Engineering Associates, Inc., and USDA Natural Resources Conservation Service. 2001. "Impact of Soil Disturbance During Construction on Bulk Density and Infiltration in Ocean County, New Jersey." Retrieved 18 May 2008 <http://www.ocscd.org/soil.pdf>

Ozgoz, E., T. Oztekin, and H. Gunal. "Assessment of Wheel Traffic Effect on Soil Compaction using a Soil Core Sampler." New Zealand Journal of Agricultural Research 49.3 (2006): 299-306.

Pitt, Robert, Chen, Shen-En, and Shirley Clark. "Compacted Urban Soil Effects On Infiltration and Bioretention." 9th International Conference on Urban Drainage, Portland, Oregon. September 8-13, 2002.

Rawls, J.W., D.L Brakensiek, and N. Miller. "Green-ampt Infiltration Parameters from Soils Data." Journal of Hydraulic Engineering. 109 (1983): 62-70.

Regalado, C. M., et al. "Simplified Method to Estimate the Green-Ampt Wetting Front Suction and Soil Sorptivity with the Philip-Dunne Falling-Head Permeameter." Vadose Zone Journal 4.2 (2005): 291-9.

Sanchez-Giron, V., E. Andreu, and J. L. Hernanz. "Stress Relaxation of Five Different Soil Samples when Uniaxially Compacted at Different Water Contents." Soil & Tillage Research 62.3-4 (2001): 85-99.

Saxton, K. E., and W.J. Rawls. "Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions." Soil Science Society of America Journal 70 (2006): 1569–1578

Schafer-Landefeld, L., et al. "Effects of Agricultural Machinery with High Axle Load on Soil Properties of Normally Managed Fields." Soil & Tillage Research 75.1 (2004): 75-86.

Shestak, C. J., and M. D. Busse. "Compaction Alters Physical but Not Biological Indices of Soil Health." Soil Science Society of America Journal 69.1 (2005): 236-46.

Spoor, G. "Alleviation of Soil Compaction: Requirements, Equipment and Techniques." Soil Use and Management 22 (2006):113-122.

Taylor, H. M, et al. "Soil Strength-Root Penetration Relations for Medium-to Coarse Textured Soil Materials." Soil Science 102.1 (1966): 18-22.

Urban, A.L., S. L. Hettiarachchi, K. F. Miller, G. P. Kincaid, and J. S. Gulliver. "Field Experiments to Determine Gas Transfer at Gated Sills." Journal of Hydraulic Engineering 127(2001): 848-859.

Wadsworth, H.M. Handbook of Statistical Methods for Engineers and Scientists. New York: McGraw-Hill., 1990.

Washington State Department of Ecology (WDOE). 2007. "Building Soil: Guidelines and Resources for Implementing Soil Quality and Depth BMP (T5.13)." WDOE Stormwater Management Manual for Western Washington. Washington State Department of Ecology, Seattle, Washington.

Web Soil Survey. United States Department of Agriculture, National Resources Conservation Service. 2009. Accessed June 2010 <http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm>

Yoo, G. Y., T. M. Nissen, and M. M. Wander. "Use of Physical Properties to Predict the Effects of Tillage Practices on Organic Matter Dynamics in Three Illinois Soils." Journal of Environmental Quality 35.4 (2006): 1576-83.

Appendix A

Soil Properties

A.1 Soil Core Information

One soil core was collected from each plot from every site. Each core was photographed and analyzed for soil texture using a feel-test method and for soil color using a Munsell® Color Chart

A.1.1 Clifton E. French Regional Park

Soil core information is provided on the next few pages.

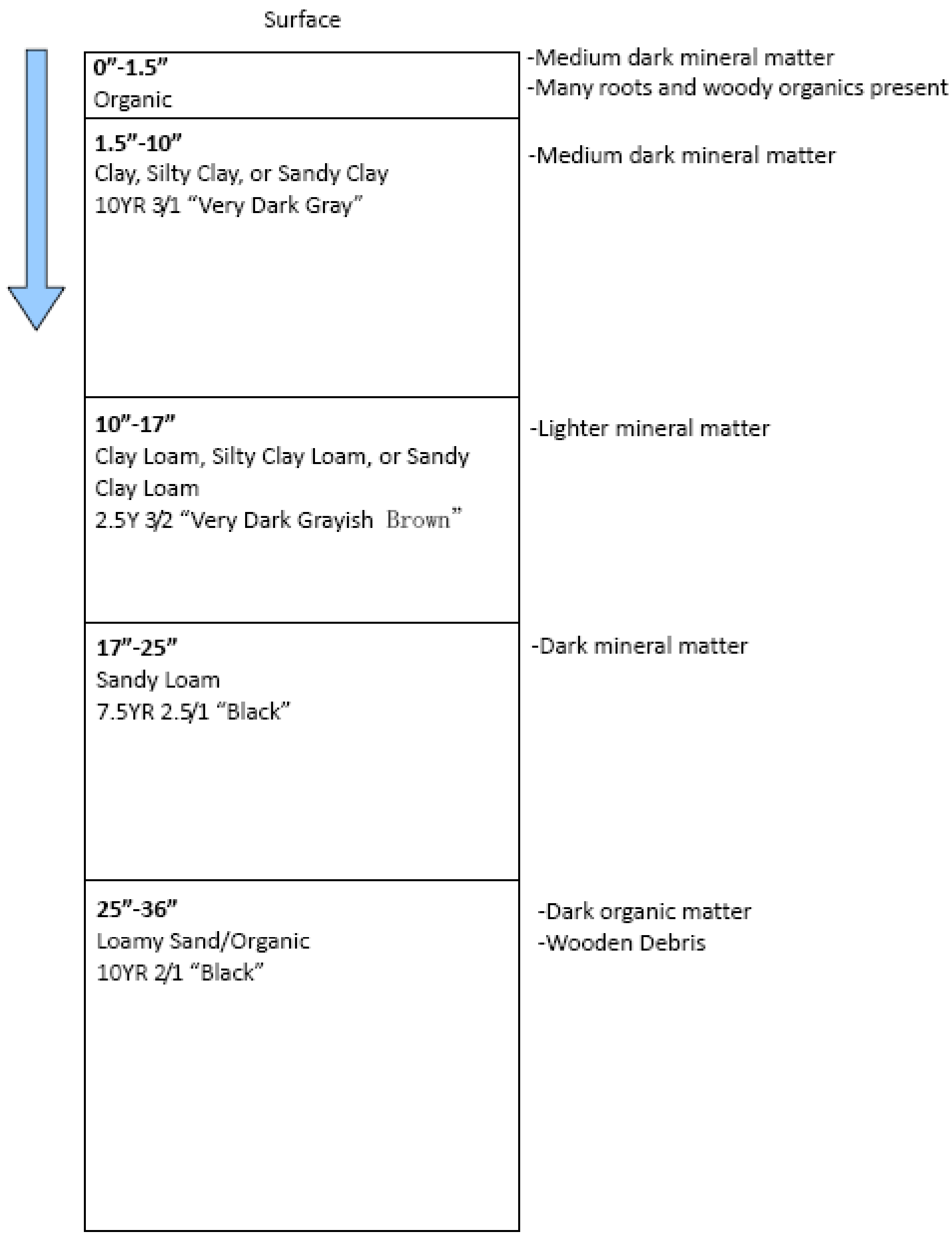

Figure A.1.1 Control plot soil core at French Regional Park.

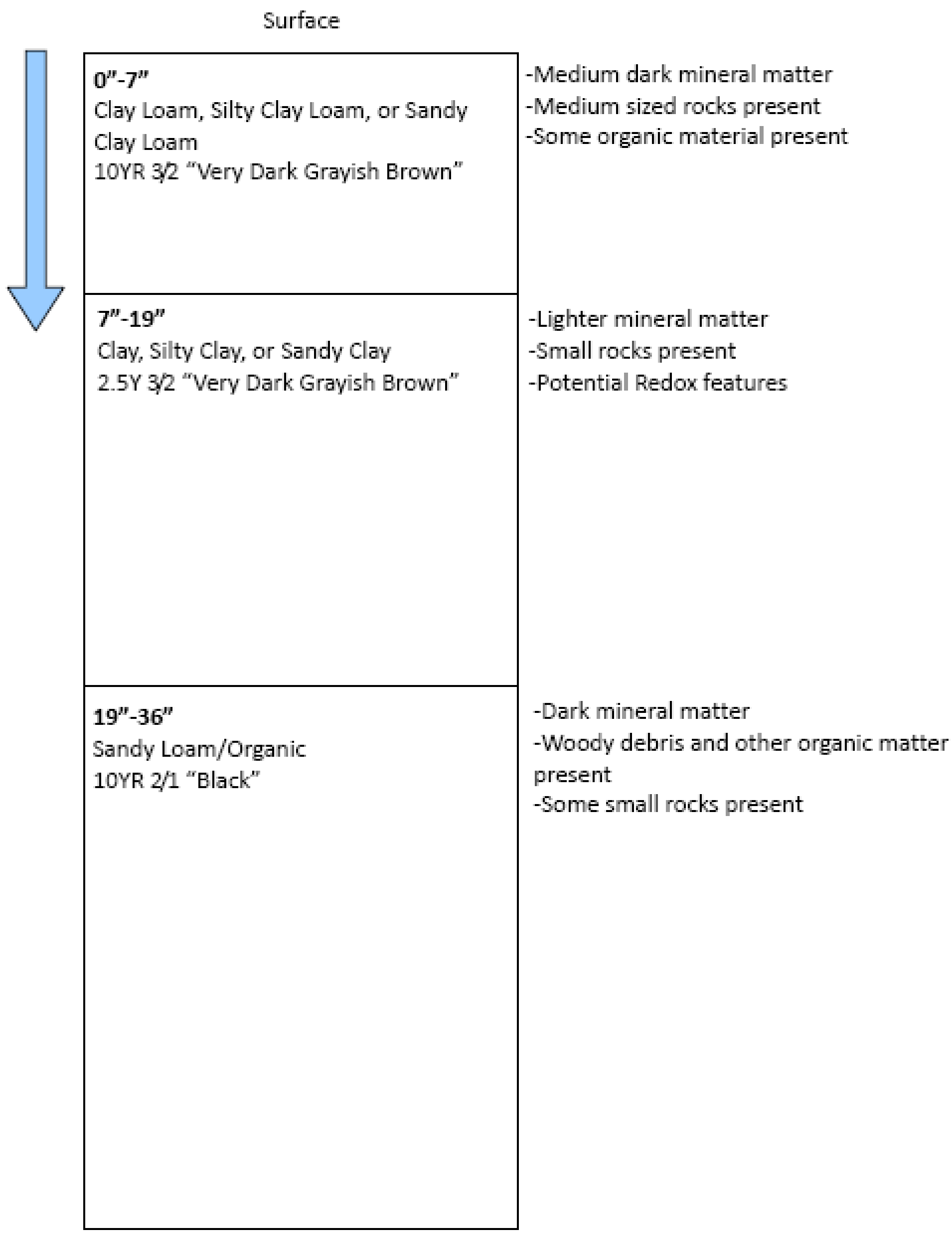

Figure A.1.2 Till plot soil core at French Regional Park.

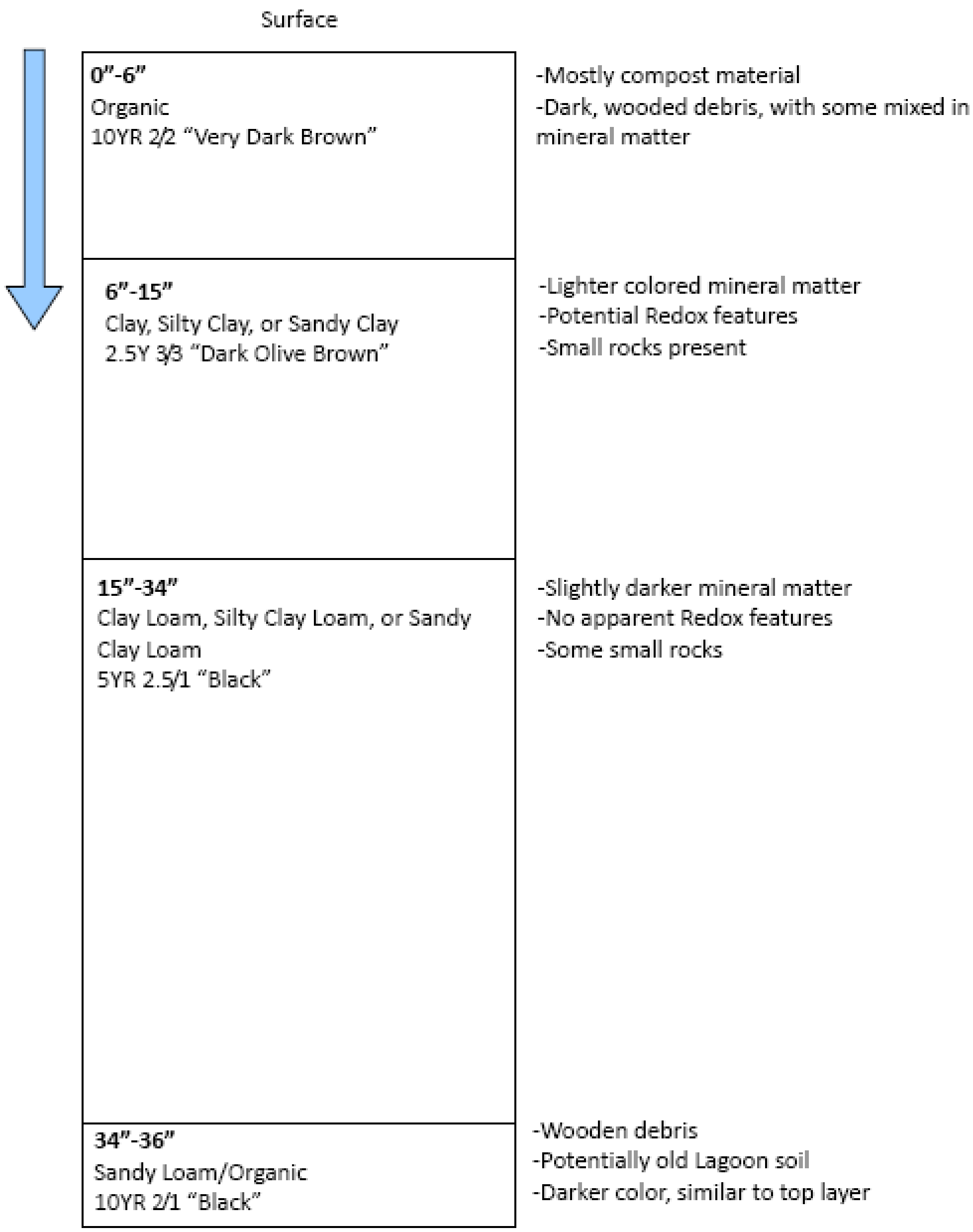

Figure A.1.3 Compost plot soil core at French Regional Park.

Figure A.1.4 Photograph of control plot soil core at French Regional Park.

Figure A.1.5 Photograph of till plot soil core at French Regional Park.

Figure A.1.5 Photograph of compost plot soil core at French Regional Park.

A.1.2 Lake Minnetonka Regional Park

Soil core information is provided on the next few pages.

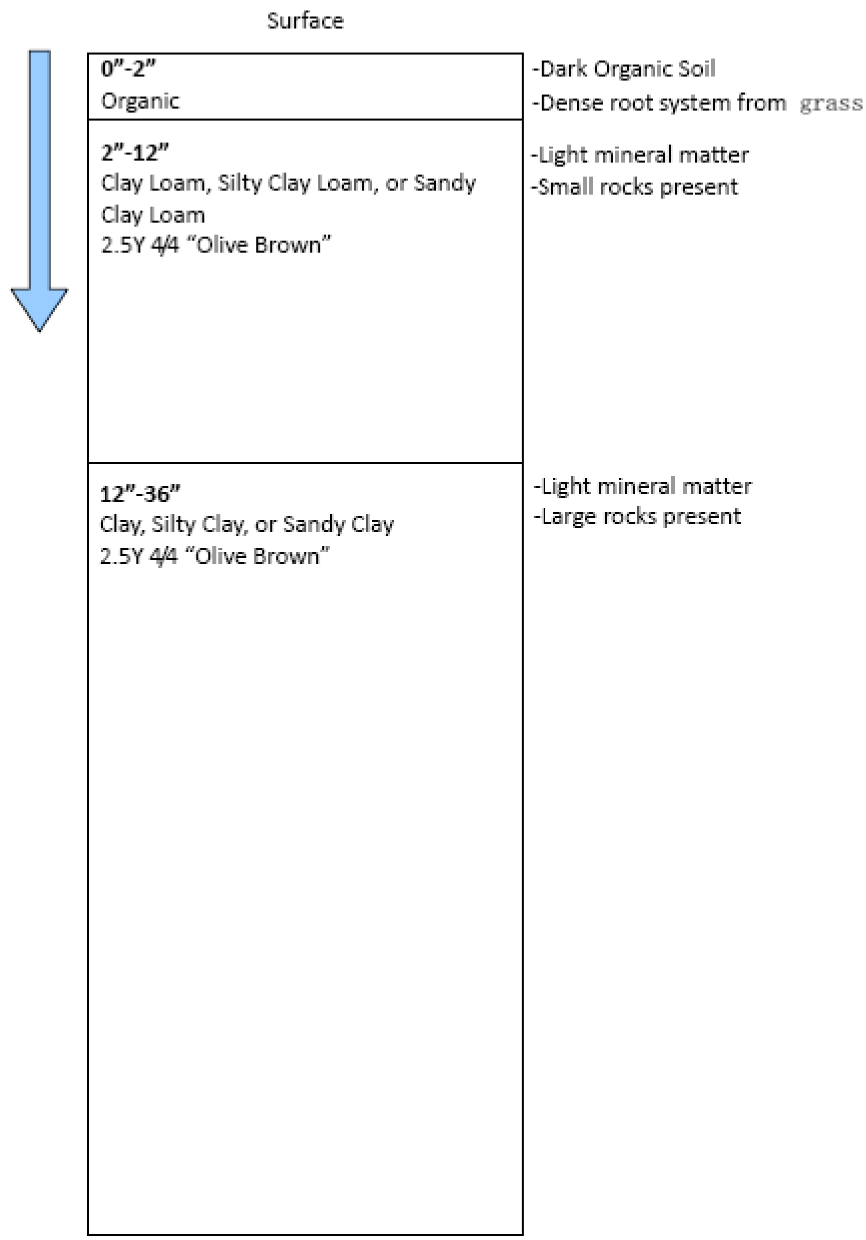

Figure A.1.6 Control plot soil core at Lake Minnetonka Regional Park.

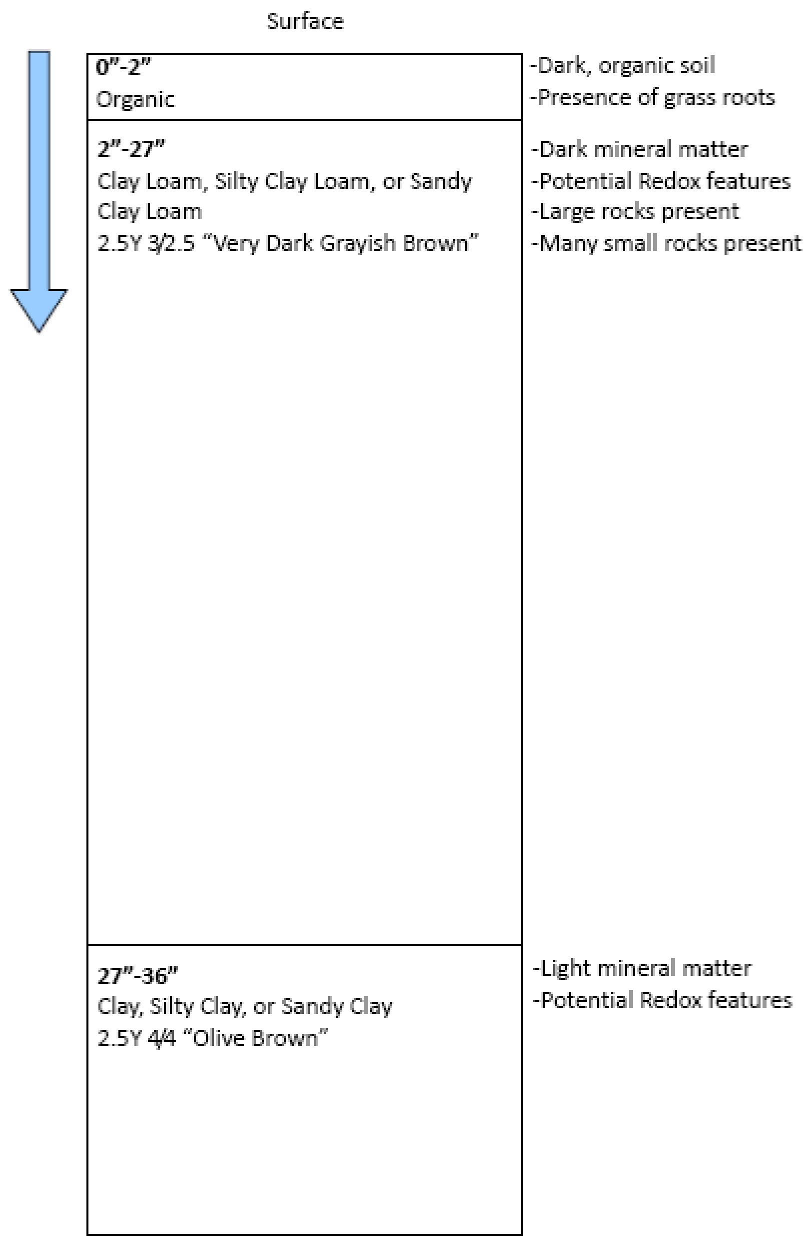

Figure A.1.7 Till plot soil core at Lake Minnetonka Regional Park.

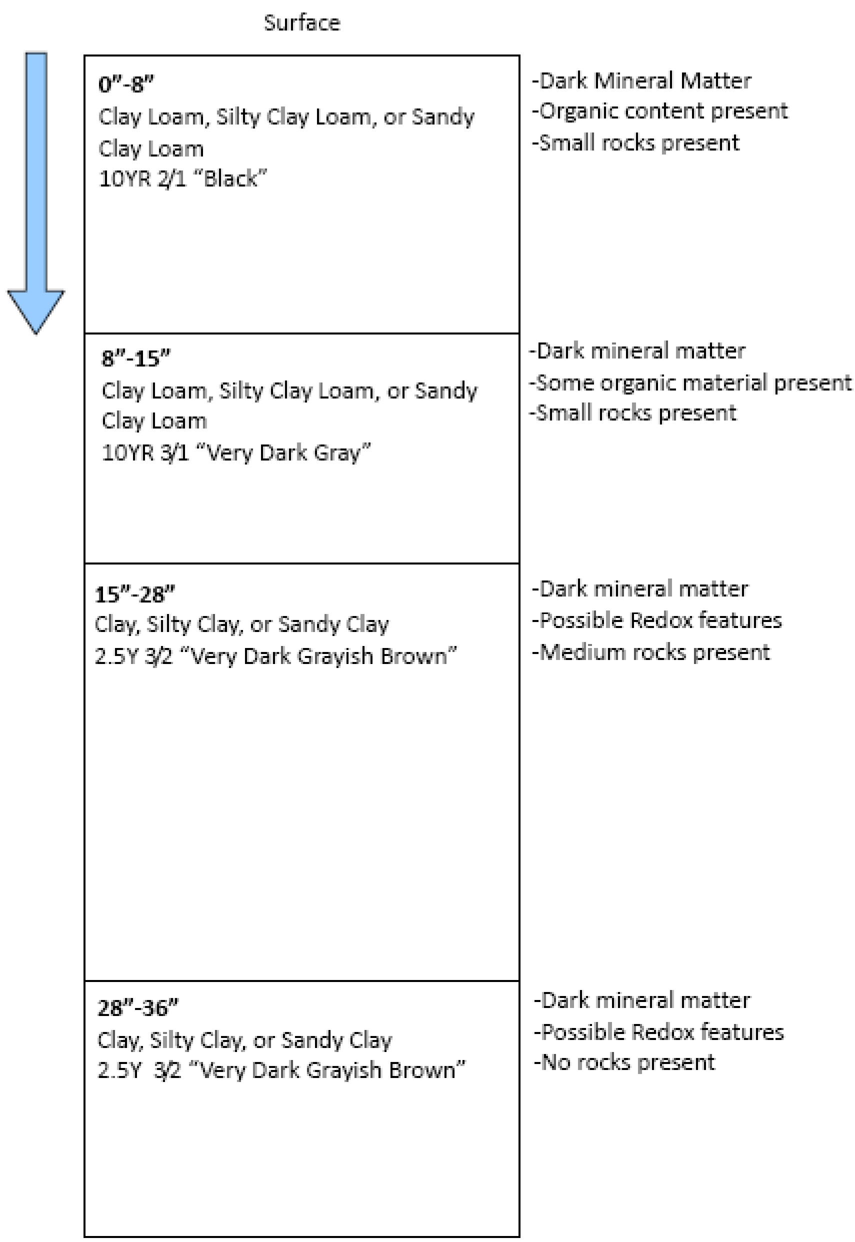

Figure A.1.8 Compost plot soil core at Lake Minnetonka Regional Park.

Figure A.1.9 Photograph of control plot soil core at Lake Minnetonka Regional Park.

Figure A.1.10 Photograph of till plot soil core at Lake Minnetonka Regional Park.

Figure A.1.11 Photograph of compost plot soil core at Lake Minnetonka Regional Park.

A.1.3 Maple Lakes Park

Soil core information is provided on the next few pages.

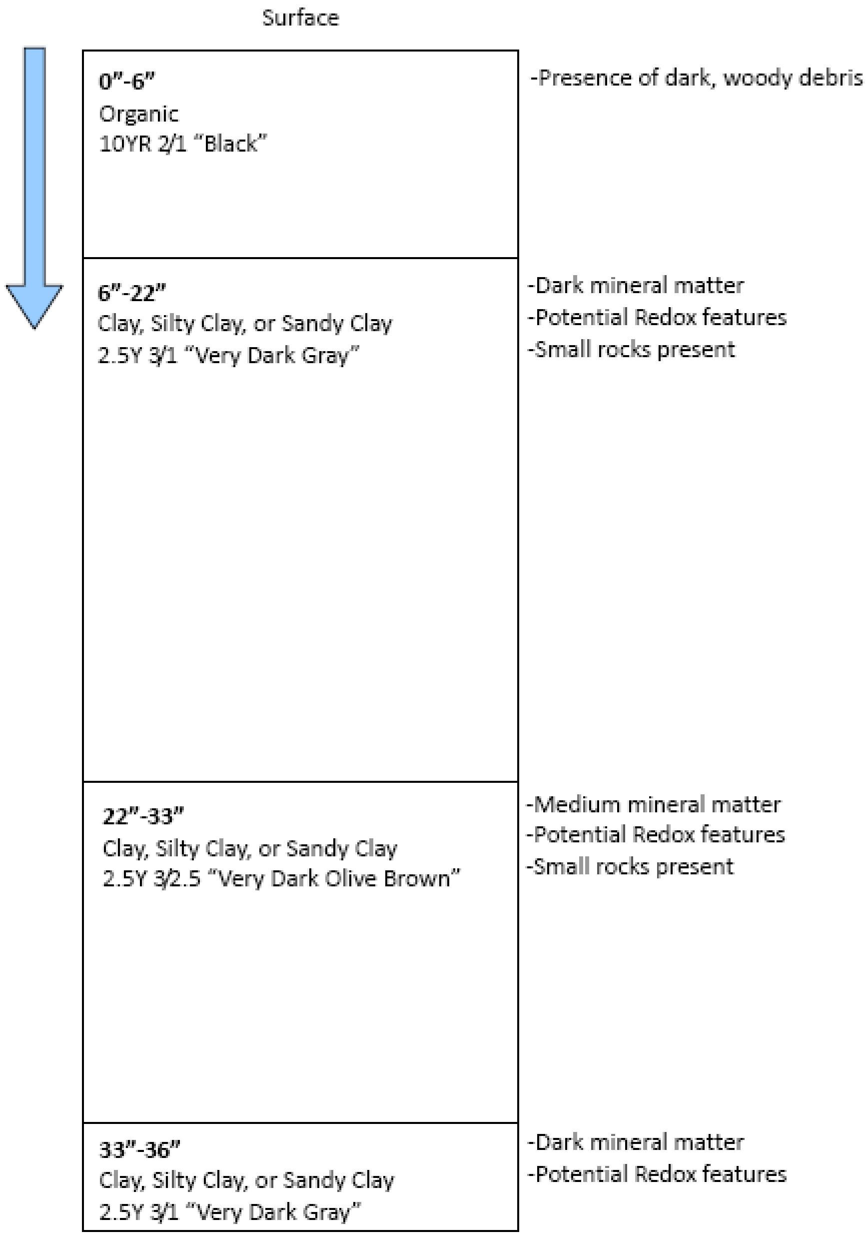

Figure A.1.12 Control plot soil core at Maple Lakes Park.

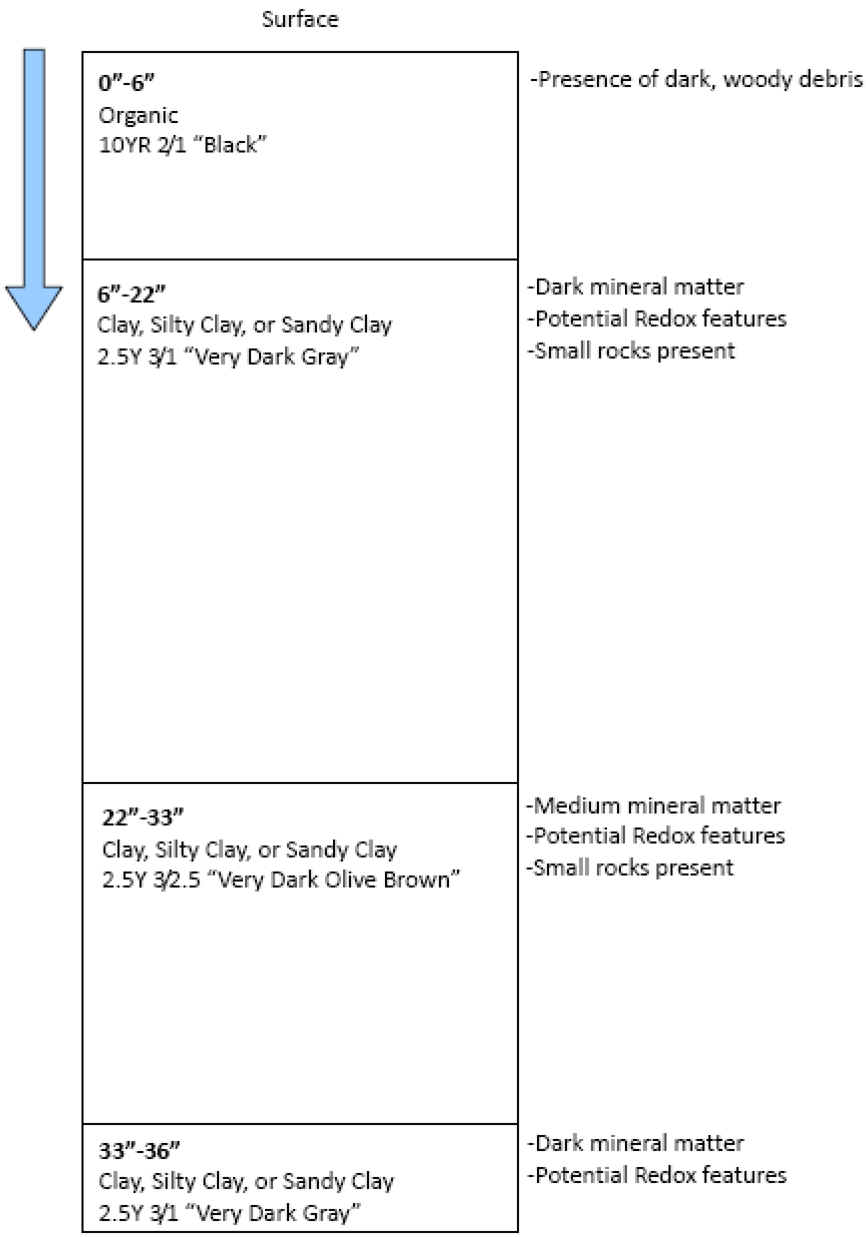

Figure A.1.13 Till plot soil core at Maple Lakes Park.

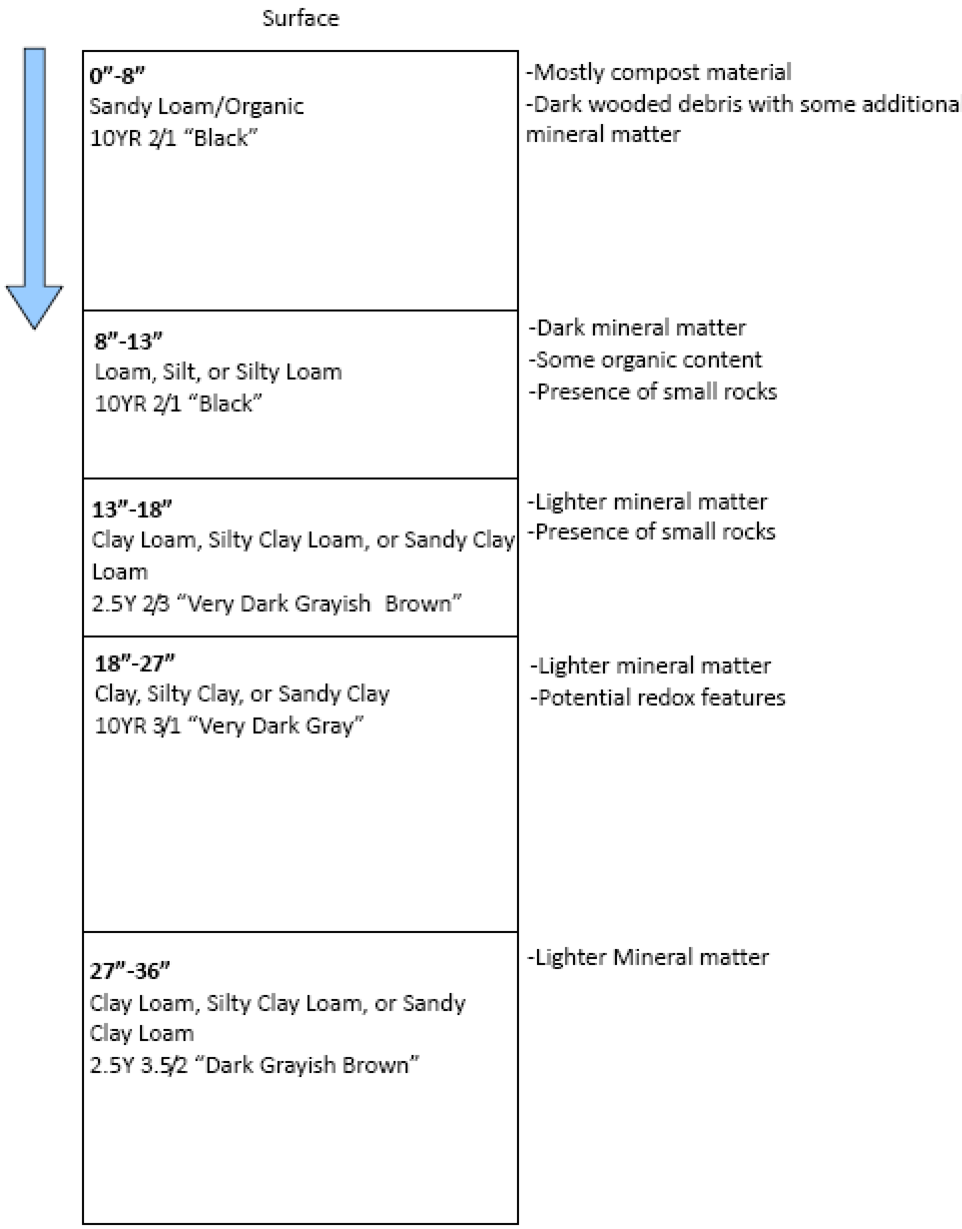

Figure A.1.14 Compost plot soil core at Maple Lakes Park.

Figure A.1.15 Photograph of control plot soil core at Maples Lakes Park.

Figure A.1.16 Photograph of till plot soil core at Maples Lakes Park.

Figure A.1.17 Photograph of compost plot soil core at Maples Lakes Park.

A.2 Compost Composition

The following information provided is a lab report analysis of the compost used in this study. The compost was provided by Plaisted, Inc. and was analyzed by Soil and Plant Laboratory, Inc. The lab report is provided on the next few pages.

Soil & Plant Laboratory, Inc
Leaders in Soil & Plant Testing Since 1946
www.soilandplantlaboratory.com

Orange Office
Report No. 08-312-0002
December 5, 2008

Plaisted Companies Inc.
11555-205th Avenue
P.O. Box 332
Elk River, MN 55330

Attn: Kerry Glader

Re: **LEAF COMPOST SAMPLE**

Attached are the data sheet and the Germination Percentage report for the leaf compost sample which was received for testing at the laboratory on November 7 of this year. It was requested that this material be compared with the Minnesota DOT Spec 3890-4, Section B that describe compost specification.

Test Results

The leaf compost meets the specifications for organic content which indicates the minimum organic in the mater must be 30% or higher.

The leaf compost carbon/nitrogen ratio is slightly above the specification guidelines which indicate it should be between 6:1 and 20:1. The material meets the specifications for pH. Moisture content is slightly below the 35% minimum and the bulk density is within specification guidelines. Salinity is adequately low and the particle size distribution is favorable. The material also passes the germination test for lettuce seed.

Increasing slightly both the moisture content and total nitrogen content of this batch of leaf compost should result in a material that meets the Minnesota DOT requirements.

Please do not hesitate to contact us if you have additional questions regarding the testing process. I apologize for the germination test results being forwarded to you without the remainder of the analytical testing attached.

JOHN E. RODEBAUGH, Ph.D.

JER: dlb

Soil & Plant Laboratory, Inc.

Leaders in Soil & Plant Testing Since 1946

352 Mathew Street Santa Clara, CA 95050 408-727-0330 (phone) 408-727-5125 (fax)

www.soilandplantlaboratory.com

COMPOST / AMENDMENT EVALUATION

Send To : Plaisted Companies PO Box 332 Elk River MN 55330	Project : Leaf compost	Report Number : **08-312-0002** Customer Number : 00473 Date printed : 11/21/2008 Date received : 11/07/2008 Page : 1 of 1 Lab Number : 12432

Sample Id : **leaf compost sample**

Nutrient	Total - Dry Weight	Extractable - Dry Weight	Saturation Extract	Sufficiency Factor
Nitrogen (N)	1.01 %			
NH_4-N				
NO_3-N				
Phosphorus (P)				
Phosphorus (P_2O_5)				
Potassium (K)				
Potassium (K_2O)				
Calcium (Ca)				
Magnesium (Mg)				
Sodium (Na)				
Sulfur (S)				
Sulfate (SO_4)				
Chloride (Cl)				
Copper (Cu)				
Zinc (Zn)				
Manganese (Mn)				
Iron (Fe)				
Dilute Acid Fe		0.07 %		
Boron (B)				

Test	Result
pH (sat paste)	7.2 s.u.
% Half Sat.	53
TEC	
Qualitative Lime	
Salinity (EC of sat ext.)	4.3 dS/m
SAR (Sodium adsorption ratio)	
Sodium as % of ECe	
Bulk Density - Dry	1008 lbs/yd³
Bulk Density - As Received	1534 lbs/yd³
Moisture - As Received	34.3 %
Organic	44.8 %
Weight of organic / yd³	451 lbs/yd³
Weight of mineral / yd³	556 lbs/yd³
C/N Ratio	26.6

Gradation	
Wt Percent Retained 1"	0.0 %
Wt Percent Retained 1/2"	4.3 %
Fraction Passing 1/2 inch Screen - Dry Weight Basis	
Screen Opening	**% Passing**
Passing 9.5mm	98.4 %
Passing 6.4mm (1/4")	90.1 %
Passing 4.75mm	86.2 %
Passing 2.36mm	75.5 %
Passing 1.00mm	57.9 %
Passing 0.50mm	34.7 %

Soil & Plant Laboratory, Inc
Leaders in Soil & Plant Testing Since 1946
www.soilandplantlaboratory.com

Orange Office
Lab No. 08-312-0002
December 4, 2008

Plaisted Companies, Inc.
P.O. Box 332
Elk River, MN 55330

Attn: Kerry Glader

COMPOST SEEDLING BIOLOGICAL ASSAY

A seedling bioassay was performed on a leaf compost sample received by Soil and Plant Laboratory on November 6, 2008. As requested, 2 assays were performed on the sample; one using cucumber seeds and the second with seeds of loose head lettuce var. 'Black-Seeded Simpson' from Burpee Seed.

The requested assays were performed according to STA Method 05.05-A. Briefly, this consisted in sowing the seeds in 3 adjacent 9-cell rows of a plug tray with pre-moistened compost diluted 50:50 by vol. with washed, hydrated vermiculite. Positive and negative controls were also included in accordance with the afore mentioned methodology.

Test Results

Sample Id.	Type of Seed Used	% Emergence	% Seedling Vigor
11308-1000 yd-2000 yd Leaf Compost	Cucumber	104.35	100
11308-1000 yd-2000 yd Leaf Compost	Lettuce	100.00	56.41

Comments

The quality of the germinated cucumber seedlings was excellent and in fact most of the seedlings appeared more vigorous and were of greater height compared to the positive control. As for the lettuce seedlings the compost group was stunted and chlorotic compared to the positive control.

Please call if you have any questions.

Paul F. Santos, M.S.
Plant Pathologist
Email: kerry@plaistedcompanies.com

Soil & Plant Laboratory, Inc
Leaders in Soil & Plant Testing Since 1946
www.soilandplantlaboratory.com

Orange Office
Lab No. 08-346-0007
December 18, 2008

Plaisted Companies Inc.
11555-205 Ave
P.O. Box 332
Elk River, MN 55330

Attn: Kerry Glader

Re: LEAF COMPOST SAMPLE (11308-1000 +2000 yd Finished Compost)

Attached is the data sheet for the fertility levels found in this compost sample, which was received for testing at the Laboratory on November 7.

Fertility Levels

This material is near neutral in reaction and salinity is slightly excessive if it were to be used without dilution as a growing medium. Typically a material of this type would be only one of the bulk ingredients in a mix and this would reduce the fertility levels including the salinity.

The available nitrogen is in a very good range while phosphorus and potassium are slightly above full sufficiency and these elevated levels are contributing to the salinity excess. Calcium and magnesium levels are very good and in the micronutrient group the levels of copper, zinc and manganese are good with iron and boron slightly excessive. Sulfate is in a good range and sodium is not excessive.

Blending this material with a low fertility landscape soil at rates not exceeding 6 cubic yards per 1000 square feet of area would establish organic and fertility levels in the soil that would be quite favorable for most landscape plantings. This amount would be approximately 2 inches in depth and is typically incorporated into the upper 4-6 inches of soil prior to planting.

For a planting mix we would suggest rates of addition in the range of 25-30% by volume of the mix and this would establish good levels of fertility in the mix when combined with other low salinity, low fertility bulk ingredients. With a blend of this type only nitrogen would be needed in the maintenance fertilizer for the first several months after planting.

Please do not hesitate to contact us when we can be of additional assistance. Best Wishes for a Happy Holiday Season.

JOHN RODEBAUGH
JR:bjm

Soil & Plant Laboratory, Inc.

Leaders in Soil & Plant Testing Since 1946

352 Mathew Street Santa Clara, CA 95050 408-727-0330 (phone) 408-727-5125 (fax)

www.soilandplantlaboratory.com

SOIL ANALYSIS

Send To :	Project :	
Plaisted Companies PO Box 332 Elk River MN 55330	Leaf Compost	Report No : 08-346-0007 Cust No : 00473 Date Printed : 12/15/2008 Date Received : 12/11/2008 Page : 1 of 1 Lab Number : 13063

Sample Id : **Leaf Compost Sample 11308-1000 + 2000 yd**

SATURATION EXTRACT - PLANT SUITABILITY

Test	Result	Effect on Plant Growth: Negligible / Sensitive Crops Restricted / Many Crops Restricted / Only Tolerant Crops Satisfactory / Few Crops Survive
Salinity (ECe)	5.9 dS/m	
Sodium Adsorption Ratio (SAR) *	0.56	
Boron (B)	1.10 ppm	
Sodium (Na)	1.8 meq/L	
Chloride (Cl)		
Carbonate (CO3)		
Bicarbonate (HCO3)		
Fluoride (F)		

* Structure and water infiltration of mineral soils potentially adversely affected at SAR values higher than 6.

Test	Result	Strongly Acidic / Moderately Acidic / Slightly Acidic / Neutral / Slightly Alkaline / Moderately Alkaline / Strongly Alkaline	Qualitative Lime
pH	7.1 s.u.		None

EXTRACTABLE NUTRIENTS

Test	Result	Sufficiency Factor	SOIL TEST RATINGS: Very Low / Low / Medium / Optimum / Very High
Available-N	156 ppm	1.8	
Phosphorus (P) - Olsen	143 ppm	2.7	
Potassium (K)	2562 ppm	8.8	
Potassium - sat. ext.	41.8 meq/L		
Calcium (Ca)	2183 ppm	0.9	
Calcium - sat. ext.	11.3 meq/L		
Magnesium (Mg)	371 ppm	1.1	
Magnesium - sat. ext.	8.3 meq/L		
Copper (Cu)	2.3 ppm	1.2	
Zinc (Zn)	13 ppm	1.7	
Manganese (Mn)	29 ppm	1.7	
Iron (Fe)	210 ppm	2.8	
Boron (B) - sat. ext.	1.10 ppm	3.7	
Sulfate - sat. ext.	4.9 meq/L	1.6	
Exch Aluminum			

NO3-N	NH4-N	Total Exchangeable Cations(TEC)
152 ppm	4 ppm	151 meq/kg

Cu, Zn, Mn and Fe were analyzed by DTPA extract.

PARTICLE SIZE ANALYSIS

Weight Percent of Sample Passing 2mm Screen

Half Sat	Organic Matter	Gravel Coarse 5-12	Gravel Fine 2-5	Sand Very Coarse 1-2	Sand Coarse 0.5-1	Sand Med. to Very Fine 0.05-0.5	Silt .002-.05	Clay 0-.002	USDA Soil Classification
45 %									

Graphical interpretation is a general guide. Optimum levels will vary by crop and objectives.

Appendix B

Runoff Calculations

A Green-Ampt infiltration spreadsheet model was used to calculate stormwater runoff from the three plot types used in this project (control, till, and compost) using real rainfall data for Minnesota. This model was used as a tool for comparison between the plot types using the field data collected at Maple Lakes Park during the second year of assessment. This site was selected for this appendix because is showed the highest level of compaction and the highest amount of improvement from soil remediation.

B.1 Green-Ampt Infiltration Method

The Green-Ampt method was used to calculate the infiltration rate of water into a soil and to determine the amount of precipitation the soil can accommodate. It assumes a sharp wetting-front as the water infiltrates the soil and that the water moves uniformly downward in a homogeneous soil. The following equations (Mays, 2005) are used to calculate the infiltration rate (B.1.1) and the cumulative depth of infiltrated water into the soil (B.1.2). These equations assume that any amount of water that ponds on the surface is converted directly to runoff.

$$f(t) = K_{sat}\left[\frac{\psi\Delta\theta}{F(t)} + 1\right] \qquad \text{(B.1.1)}$$

$$F(t) = K_{sat}t + \psi\Delta\theta \ln\left[1 + \frac{F(t)}{\psi\Delta\theta}\right] \quad \text{(B.1.2)}$$

where,

f(t) is the infiltration rate at time equal to t [cm/hr]

F(t) is the cumulative depth of water infiltrated a time equal to t [cm]

K_{sat} is the saturated hydraulic conductivity of the soil [cm/hr]

ψ is the wetting front suction of the soil [cm]

$\Delta\theta$ is the change in volumetric moisture content across the wetting front [cm^3/cm^3]

If the rainfall intensity, i(t), is greater than or equal to Ksat, then there is a potential for the rainfall to pond on the surface of the soil. If the depth of infiltrated water, F(t=t), is less than the depth of rainfall during a time interval of rainfall intensity then runoff will be generated. This can be found by letting i(t) = f(t) and calculating F(t). Excess rainfall depth is found by subtracting the amount infiltrated from the rainfall depth. This is the depth of runoff.

B.2 Model Inputs

Runoff was calculated using four design storms under different initial conditions. The design storms were created using "Rainfall Frequency Analysis Atlas of the Midwest" (Huff and Angel, 1992). This report uses real rainfall data from Minnesota to give values for the precipitation depth for different storm durations and return periods. Huff and Angel (1992) also provide a table that gives the cumulative duration of the storm versus the cumulative amount of storm rainfall. This was used to generate the rainfall intensity for different time intervals during the storm event. Return periods of 2 years, 10 years, 25 years, and 100 years were selected. A one-hour storm duration was chosen because most runoff from turf areas will likely be generated from short, high intensity storm events (Pitt et al., 2002). This is due to the infiltration capacity of the soil near the surface being quickly exceeded (Pitt et al., 2002). 24-hour storms were considered for this appendix, but most of these duration storms had rainfall intensities less than the saturated hydraulic conductivity of the soil, which would not result in runoff.

Two initial soil conditions were analyzed in the model. One condition was related to the average volumetric moisture content change found at Maple Lakes Park ($\Delta\theta$ ~0.3). The other condition simulated was a soil that was near its saturated moisture content ($\Delta\theta$ ~0.1). This second condition could result from a recent storm previous to the simulated storm event, which would leave the soil moist. These conditions control the storage capacity of the soil. The case with a large change in volumetric moisture content allows more water to infiltrate before ponding can occur.

Another case considered in the model was amount of connected impervious surface to the pervious plot area. To simulate this, an intensity factor was used to multiple the rainfall intensity during each interval of the storm. For instance, if the impervious area connected to the plot area were of the same size then the intensity factor would be two. This assumes that all of the precipitation falling on the impervious area moves to the pervious turf area and effectively doubles the rainfall intensity on the plot. An intensity factor of one implies that there is no connected impervious area to the plot.

Finally, inputs for the saturated hydraulic conductivity (Ksat) and the wetting front suction (ψ) used in the Green-Ampt model were obtained from field measurements using the Modified Philip-Dunne Permeameter (MPD). The geometric mean of Ksat and the average ψ are given in Table B.2.1 for each plot type.

Table B.2.1 The inputs of Ksat and ψ for different plots types at Maple Lakes Park.

Plot:	**Ksat**	**ψ**
	[cm/hr]	[cm]
Control	1.94	14.83
Till	4.43	16.19
Compost	11.15	10.7

B.3 Results

Different scenarios for the Green-Ampt model were created using different design storms, moisture conditions, and intensity factors. The results of the model for different scenarios are given in Table B.3.1.

Table B.3.1 The portion of precipitation that resulted in runoff for Green-Ampt model. Applied to plots in Maple Lake Park, Maple Grove, Minnesota.

Design Storm:	Precipitation [cm]	Δθ	Intensity Factor	Portion of Precipitation that Results in Runoff (%)		
				Control Plot	Till Plot	Compost Plot
2 yr, 1 hr	3.18	0.1	1	13.3	0.0	0.0
2 yr, 1 hr	3.18	0.1	2	88.9	38.3	3.0
2 yr, 1 hr	3.18	0.3	1	0.0	0.0	0.0
2 yr, 1 hr	3.18	0.3	2	51.8	4.0	0.0
10 yr, 1 hr	4.39	0.1	1	28.4	3.3	0.0
10 yr, 1 hr	4.39	0.1	2	113.4	66.5	19.2
10 yr, 1 hr	4.39	0.3	1	7.8	0.0	0.0
10 yr, 1 hr	4.39	0.3	2	82.2	32.0	2.1
25 yr, 1 hr	5.18	0.1	1	36.1	9.3	0.0
25 yr, 1 hr	5.18	0.1	2	125.3	81.0	32.5
25 yr, 1 hr	5.18	0.3	1	15.9	0.0	0.0
25 yr, 1 hr	5.18	0.3	2	95.5	47.3	7.6
100 yr, 1 hr	6.53	0.1	1	45.5	20.4	2.0
100 yr, 1 hr	6.53	0.1	2	139.5	98.0	52.5
100 yr, 1 hr	6.53	0.3	1	27.3	2.4	0.0
100 yr, 1 hr	6.53	0.3	2	114.8	69.5	25.4

The results show that the control plot led to higher percentages of runoff from the rainfall than the till or compost plot. In four cases, the one-hour event with an intensity factor of two, the control plot could not accommodate all of the runoff from the connected impervious area. This resulted in 113.4% to 139.5% of runoff from the precipitation. The average percent of runoff from all of these scenarios for the control, till, and compost plots were 61.6%, 29.5%, and 9.1% respectively. The runoff generated by the compost plot was ~1/6 that of the runoff in the control plot and ~1/3 of the runoff in the till plot. These results show that soil remediation can effectively reduce the amount of runoff from short, high intensity storms.