Rehabilitation of Severely Compacted Urban Soil to Improve Tree Establishment and Growth

Rachel Montgomery Layman

Thesis submitted to the Faculty of the **Virginia Polytechnic Institute and State University** in partial fulfillment of the requirements for the degree of

Master of Science

in

Horticulture

J. Roger Harris (Co-chair)
Susan D. Day (Co-chair)
W. Lee Daniels
P. Eric Wiseman

December 2, 2010
Blacksburg, Virginia

Keywords: canopy; tree roots; minirhizotron; organic amendment; subsoiling; urban forestry

Rehabilitation of Severely Compacted Urban Soil to Improve Tree Establishment and Growth

Rachel M. Layman

Abstract

Land development restricts tree growth by damaging soil structure and removing organic matter. Mechanical loosening and organic amendment may improve soil physical properties and tree establishment and growth. Effects of typical post-construction practice and improved methods of soil restoration on tree growth and soil properties were evaluated over two years. Treatments included undisturbed soil (UN); minimum effort (ME) (10 cm topsoil); enhanced topsoil (ET) (ME + rototilling); and profile rebuilding (PR) (compost, subsoiling, topsoil and rototilling). Pretreatment included removing topsoil and compacting subsoil to 1.95 g/cm^3 bulk density. *Acer rubrum* L. (red maple), *Quercus bicolor* Willd. (swamp white oak), *Ulmus* 'Morton' *(Ulmus japonica* (Rehd.) *Sarg.* x *Ulmus wilsoniana* Schneid.) (Accolade® elm), *Prunus* 'First Lady' *(Prunus xincam* x *Prunus campanulata)* L. and *Quercus macrocarpa* Michx. (bur oak) were planted in each plot. The PR treatment reduced soil bulk density at 15-20 cm depth and increased soil C/N ratio, pH, and fertility. Mean canopy projection and cross-sectional trunk area in PR plots ranged from 32% to 226% and 16% to 71%

greater, respectively, than those in ME plots. PR treatment increased *Q. bicolor* photosynthesis. Greater root presence was observed in deeper soil layers of ET and PR treatments for *A. rubrum* and of UN and PR for *Q. bicolor;* root distribution was not measured for other species. Rehabilitation improved soil physical properties and tree growth after two years. Species variation in growth rate and environmental tolerance may influence early growth treatment effects. Long-term data is needed to fully understand effects of rehabilitation.

Dedication

This thesis is dedicated with deep gratitude to God for providing far more than I truly need in life. He has given me an abundance of encouragement and help throughout the pursuit of my Master of Science degree, especially through my loving and supportive Mother and Father. May this effort and degree be used to serve others and always bring glory and honor to Him.

Author's Acknowledgements

First and foremost, I would like to thank my Committee Co-Chairs, Dr. J. Roger Harris and Dr. Susan D. Day for their guidance, unlimited time, and friendship throughout the past four years. I could not have been more fortunate to have been offered this project with them and am very grateful to them for allowing me to study under their mentorship. Dr. Harris' and Dr. Day's abundance of knowledge and genuine desire for me to learn was a blessing. Their patience and understanding of my work schedule could not have been greater. I am also very thankful for the contributions and advice provided by my Committee Members, Dr. Daniels and Dr. Wiseman. I am especially appreciative of the time they took to provide thorough reviews of my proposal and thesis.

The flexibility and understanding from my boss, Marc Hrovatic, at Luna Innovations Incorporated was also a blessing. I could have never completed this effort without his support.

My research would never been possible without the many hours of assistance from Kentland Farm under the kind leadership of John Wooge. Many hours and efforts by Chad Keith, Jerry Stump, Tommy Sowers and Forest Davis during the labor intensive site installation and site maintenance was greatly appreciated. I am also grateful for the Urban Horticulture Center for providing the container-grown trees and various equipment. Thanks to Dr. Jersey Novak, Moore's Farm and Kentland Farm for funding and installing the greatly envied deer fence. Thanks to the Department of Forest Resources and Environmental Conservation for the use of the Urban Forestry Lab and their equipment. I am also grateful to the Department of Crop Soil and Environmental Science Soil Labs and Julie Burger and Steve Nagle for the various soil

analyses completed. A very special thanks is due to Fernando Richmond from Costa Rica for his many hours helping me collect and grind soil samples and for his especially pleasant disposition.

I especially want to thank the Department of Horticulture for two semesters of Graduate Teaching Assistantships, without which I could never have made the jump to begin this pursuit. It was a privilege to learn from and assist Dr. Harris and Dr. Alex Niemiera. Many thanks are also due to Dr. Harris for allowing me the use of his old office, Room 401-C, where my most productive work took place these last few months.

My research involved the assistance of various Research Associates: Velva Groover, Sara Gugercin, John James and John Peterson. I greatly appreciate all of their assistance, especially with data collection. I am also deeply grateful for many close friends and fellow graduate students who helped at my site or provided ongoing genuine interest and encouragement! I owe a very big, warm, heartfelt thanks to Linda Taylor and Juan Ruiz who were always there with a helping hand or ear throughout the coursework, teaching assistantship, research and everyday life! Ernestine Foresman, my WLP Mentor, was also a great source of encouragement from the time I met her the first year of my graduate program.

Finally, I am most deeply appreciative of the loving support and assistance from my parents, John and Jane Layman; my Aunt and Uncle, Margie and Wesley Forte; and my Uncle Max Brugh. My parents proved to be my best backup for assistance in the field.

This work was partially funded by the TREE Fund. Their support is gratefully acknowledged. I am also grateful for the in-kind contributions of Deep Root Barrier and Schmidt Trees.

Table of Contents

List of Tables

List of Figures

Chapter One: Introduction and Literature Review

1.1 Introduction

Methods for restoring soil damaged by urbanization are needed to help cities and towns realize the benefits of urban trees. Urban trees have been recognized for centuries for their social and economic benefits and are increasingly being recognized as vital tools for improving and restoring urban environmental quality (Nowak et al. 2001; Zhu 2008). Healthy urban trees have become integral components of urban infrastructure and sustainable community environments. Their canopy reduces stormwater runoff, improves local air, soil and water quality, tempers climate, conserves energy and provides wildlife habitat and various aesthetic qualities (McPherson 2001). Achievement of desired benefits is dependent on the ability of urban trees to first establish well and then to develop healthy large canopies, whose benefit has been valued at up to as much as eight times as the costs for caring for them (Geiger 2004).

By the early twentieth century, many large cities and medium-sized communities in the United States had initiated programs to plant and care for street and park trees. The U.S. government enacted the Cooperative Forestry Assistance Act in 1978 which officially recognized the contribution of urban and community forests to "improve the quality of life for residents, enhance the economic value of residential and commercial property, improve air quality, reduce the buildup of carbon dioxide, mitigate the heat island effect in urban areas and contribute to the social well-being and sense of community" (Cooperative Forestry Assistance Act, 1978). The Act established provisions for federal and state cooperation in rural and community tree planting and management programs. In 1990, the America the Beautiful Act increased funding for urban forestry and further promoted public awareness of trees and tree

planting projects (America the Beautiful Act 1990). Today, city and town planners and land developers are more systematically incorporating green spaces into their development plans and establishing tree canopy goals as elements of local law such as city and town ordinances to facilitate achievement of the desired benefits as well as provide restorative functions in urban environments. However, despite such growing initiatives, urban tree removal continues, survival and growth rates of new trees remain low and a large number of urban trees die within the first several years of planting (Bernatzky 1974; Foster and Blaine 1978; Nowak et al. 1990).

The challenges for urban tree survival and growth are abundant. Limited root and canopy space, deficient or excess water and light, heat, air or soil pollution, mechanical and chemical damage, improper tree selection, lack of adequate funding for proper management, and poor soil quality are factors that must be considered (Beatty and Heckman 1981). The greatest, frequently recognized, limiting factor for tree survival and growth is poor soil quality (De Kimpe and Morel 2000). In urban settings, construction activities necessary for land development (grading, compaction and heavy equipment trafficking) severely compact soil and remove organic matter (Randrup and Dralle 1997). Similar to the problems posed by heavy equipment and management practices on plant growth in agricultural and forested environments, these typical urban soil conditions can restrict root growth of urban trees and prevent them from attaining the size and longevity needed to sustainably supply the intended environmental benefits (Day and Bassuk 1994). Optimal tree growth and canopy development depends on the ability of roots to penetrate the soil to acquire nutrients, oxygen and water. With more than 50% of world population currently living in urban areas and world populations on the rise, both transition of rural land to developed urban land uses and economic redevelopment (brownfield restoration, revitalization of towns and cities, etc.) are expected to continue for the foreseeable future (Macie and Hermansen

2002) resulting in continued soil damage. Kozlowski (1999) conveyed a growing concern that the severity of human-induced soil compaction would increase with growing world populations and continue the adverse effects of population increases on growth and yield of woody plants.

The current study is the initial two-year phase of a long-term soil rehabilitation experiment to evaluate typical practice and more involved soil rehabilitation methods for urban soils damaged by construction. This study will evaluate their effects on soil physical properties, tree establishment, root development and other growth parameters for five tree species on a graded and compacted site.

1.2 Review of Literature

Limitations of Urban Soil

Urban soil is defined by DeKimpe and Morel (2000) as soil under strong human influence in the urban and suburban landscape. Poor soil quality is frequently reported as the greatest limiting factor for optimal tree survival and growth, and urban soil quality has become the subject of much interest and research (De Kimpe and Morel 2000; Huinink 1998; Jim 1998; Karlen et al. 1997; Pouyat 2007; Scharenbroch et al. 2005; Schindelbeck et al. 2008; Vrscaj et al. 2008). Characteristics of urban soil, summarized by Craul (1985), include "great vertical and spatial variability; modified soil structure leading to compaction; presence of a surface crust on bare soil that tends to be water-repellent; modified soil reaction (usually elevated); restricted aeration and water drainage; interrupted nutrient cycling; presence of anthropeic materials and other contaminants; and modified soil temperatures regimes." Scharenbroch et al (2005) observed increased soil bulk density, reduced microbial biomass and activity, and reductions in organic matter in soils that had been affected by anthropogenic activities within the previous ten

years. Especially detrimental are soil compaction and organic matter removal, both related and incidental to urban land development activities such as clearing vegetation, grading soil, vibration and trafficking by heavy equipment.

Urban Soil Compaction.

Soil on construction sites is commonly compacted, and soil structure is therefore damaged (Alberty et al. 1984; Patterson 1977; Randrup 1997). Soil compaction results in increased soil bulk density, breakdown of aggregates, decreases in macroporosity, loss of pore continuity, increases in soil strength and reduced infiltration and aeration (Craul 1994; Kozlowski 1999). As bulk density increases, excessive soil strength results when soil dries, and inadequate aeration can result when soil is wet. While poor soil-root contact can be improved in some soils by increased bulk density (van Noordwijk et al. 1993), severe compaction-induced increases have been shown to severely limit root growth (Alberty et al. 1984; Bassett et al. 2005; Day et al. 2000; Kozlowski 1999; Patterson 1977; Smith et al. 2001; Taylor and Brar 1991; Vepraskas 1988). Healthy roots function to anchor the plant and to acquire and transport water, mineral nutrients and oxygen from the soil pores to leaves for photosynthesis. When root penetration and elongation is restricted by high bulk density, the volume of soil that can be exploited for essential nutrients and water is consequently reduced and reduced overall plant growth often results.

Daddow and Warrington (1983) summarized several efforts to characterize growth-limiting (where root growth is stopped) soil physical properties for plant roots and developed a growth-limiting textural triangle by plotting growth-limiting isodensity lines to estimate growth-limiting bulk density over the USDA soil textural triangle. This triangle provides a good visual

presentation of the strong influence of soil texture on bulk density: “soil with a large amount of fine particles (silt and clay) will have smaller pore diameters and a higher penetration resistance at a lower bulk density than a soil with a large amount of coarse particles.” For loamy soils, the triangle presents root limiting density levels of approximately 1.45-1.6 g/cm^3. As a comparison, Spoor (2006) reports bulk densities in compacted zones in landscaped areas in the range of 1.8-1.9 g/cm^3 to depths of greater than 0.8 m.

High soil strength resulting from compaction has been shown to affect root architecture (Day et al. 2010a; b). While, as Taylor and Brar (1991) point out, a change in the root system appearance does not always result in a change in aboveground growth or yield when all of the water and nutrient demands of the plant’s shoots are met, the effects of compaction on roots are site- and species-specific. Daddow and Warrington (1983) acknowledge that their triangle does not account for all factors affecting soil strength and root growth such as soil moisture, structure, and organic matter content or species-specific response to compaction, but it does provide a good aid to estimating growth-limiting bulk densities for varying soil textures.

Organic Matter Removal.

Organic matter is removed during construction activities when topsoil is removed from the development site or when vegetation is cleared. Organic matter is necessary for the development of soil structure and for sustaining water and nutrient supplies (Hillel 1982; Powers et al. 1990). Organic matter enhances soil structure development (Pagliai 2004; Zhang et al. 2005). Natural organic matter inputs can be limited in urban environments when aboveground organic matter inputs (i.e., leaves and plant debris) are removed (Sæbø and Ferrini 2006) or prevented from reaching the soil by pavement or other impervious layers. Belowground organic

matter inputs (i.e., root litter and rhizodeposition) are also reduced when root development and penetration into the soil matrix is restricted by increased bulk density and reduced macroporosity.

Urban Soil Rehabilitation Efforts

Literature regarding the effects of soil restoration on plant growth is very limited for urban environments compared to agricultural, forestry, turf, and surface mining disciplines. Methodologies appear to have been derived from these latter disciplines (Craul 1994); however, variable success in restoration of soil physical properties of compacted urban soil has been reported (Kozlowski 1999). No universal approach to ameliorating soil degradation that is equally effective for all urban environments has been identified due to the variable effects of urbanization, minimum root zone depth required (Spoor 2006) and desired benefits. Effective rehabilitation of urban soils must rely on site-specific soil characterization (Pavao-Zuckerman 2008; Spoor 2006). Furthermore, Patterson (1977) describes a soil-amending process as one that should aid in the soil improvement process (reduce compaction) over the long-term (5 to 10 years or longer).

Amelioration of compacted soil has been reported to be difficult to obtain (Horn et al. 1995; Randrup 1997). In one study, seventeen randomly selected construction sites at commercial or residential developments were evaluated and determined to have compaction levels (i.e., bulk density values) commonly regarded to be limiting to root growth. According to the contractors, loosening procedures (not specified) were implemented at 12 of the 17 sites, but positive soil loosening effects were only found occasionally (Randrup 1997). Soil bulk density in the upper 0.3 m (of reportedly loosened soil) was found to be lower than the control locations;

however, the results indicated there was no evidence for treatment effects. Similar to forest soils, large reductions of organic matter (typical at construction sites) result in short-lived positive effects of cultivation on compacted soil (Greacen and Sands 1980).

Mechanical manipulation and soil amendments have been studied as tools to improve soil conditions both around existing trees and at newly established urban landscapes. Mechanical manipulation techniques studied to loosen soil for improved root and tree growth include subsoiling (cultivation with rototillers and excavators, rippers, etc.) and air injection probes (with or without amendment slurries).

Spoor (2006) describes various equipment using narrow or winged tines and their methodologies for alleviating soil compaction. Unsuccessful attempts of alleviation were attributed to either too shallow or too deep subsoiling for the equipment used or soil conditions that did not warrant such treatment in the first place. Spoor's study emphasized that equipment used must be capable of producing different degrees of fissuring and loosening at different depths and that it must break up compacted layers before topsoil replacement. The use of shallow-leading narrow tines followed by deeper-winged tines are recommended for restoration situations, with progressively greater depth on each pass, depending on desired degree of loosening. However, no data to support the effectiveness and longevity of treatments are presented.

Moffat and Boswell (1997) evaluated the effectiveness and longevity of deep ripping using a winged tine on a restored sand and gravel mineral excavation site with the end goal of promoting deep tree rooting. Ripping to 0.5 m and 0.75 m depths were recommended for clayey and sandy sites, respectively. The widespread use of winged tines is reported, but effects are

"short-lived". In the study, bulk density reductions were limited and ripping was shown to achieve short-term soil loosening to about 0.6 meter depth.

Efforts to ameliorate soil compaction under existing vegetation is reported to be difficult due to the potential injury for root system injury (Craul 1994). Craul reviewed selected surface (aeration and rototilling) and subsurface (deep-jetting, subsoiling and trenching) compaction reduction techniques. Surface aeration makes holes in compacted soil by either creating a hole surrounded by compressed soil with a solid spike aerator or by removing a soil core with a core aerator; however, the holes are only a few inches deep and do not affect subsoil. Rototilling can be used when no trees or turf care is needed and may provide temporary loosening of the soil. When organic matter content is low, this method may reduce macroporosity (Craul 1994). Subsurface compaction reduction methodologies involve injection of air or water to fracture the compacted soil layers followed by injections of compost, fertilizer or a lighter soil into the fracture voids. Such methodologies are often used in an attempt to improve soil physical properties affecting root growth. Effectiveness of deep-jetting is reported by Craul as being influenced by texture, moisture content and other physical profile conditions and is in need of further research. Trenches can be dug radially from the trunk in the location to avoid damaging lateral roots and then filled with soil that has been amended with a high percent of organic matter. Craul concludes that radial trenching appears to be a promising technique for root system improvement of existing trees in compacted soils. Later work by Day et al (1995) found trenching resulted in greater shoot and root growth than treatments that did not involve mechanical loosening and they concluded trenching alleviates mechanical impedance and increase volumes of loosened soil for root growth.

Subsoiling in urban soil with a subsoiler or chisel plow to break up compacted layers has been limited for established trees and is most effective in newly established sites. Sinnett et al compared three cultivation techniques (2 and 4 passes using complete cultivation with an excavator bucket; one pass with a standard industrial ripper with 3 winged tines; 2-4 passes using Mega-lift prototype ripper with 5 tines) for their effect on tree establishment of 4 species on a partially restored sand and gravel extraction quarry (Sinnett 2008; Sinnett et al. 2006). All methods significantly increased maximum rooting depth and total number of roots after the fifth growing season following treatment. Complete cultivation was concluded to be the most effective method of alleviating soil compaction for tree establishment based on greater height growth and total number of roots for most species (Sinnett 2008).

Complete cultivation was also compared to a pneumatic injection method (Rolf 1994b). Subsoiling with an excavator (complete cultivation) before planting has been shown to be a successful method to speed up natural recovery process for compacted soil (Rolf 1994b). Rolf compared the effects of subsoiling with an excavator to the Terralift (pneumatic injection only, no amendment component) in two unplanted, pre-compacted sites. Topsoil was placed on the compacted soil to be treated before subsoiling with the excavator. The excavator was used to lift and break up compacted soil layers allowing the fragments to fall back into place, creating cracks in the soil. A certain amount of topsoil fills the cracks when the soil is lifted. Subsoiling with the excavator had good loosening effect on both soil types and increased growth on the sandy loam. The aeration treatment (pneumatic injection) only loosened the sandy loam and no growth increase was observed (Rolf 1994b). The best effect of the excavator treatment was observed following the second and third year according to Rolf who further concluded that the excavator can be recommended for use on most compacted soils, and is useful for small and narrow areas.

Successful urban uses of this method have been reported in the US and Sweden (Rolf 1994b). Rolf concluded the Terralift is not a universal tool for use around trees of all soil types, but can be used to relieve soil compaction in certain soils.

Another pneumatic injection device, the Terravent™ was evaluated by Hasher and Wells (2007) for its ability to increase fine root density of *A. rubrum* trees in moderately compacted clay loam urban soil. No effect was measured on fine root length for the Terravent™ treatments with or without injection of a liquid soil amendment. Smiley (2001) evaluated the effects of 30-cm Terravent™ probe injections (nitrogen gas injections followed by water solution injections) on bulk density, and no significant differences in soil bulk density were found between treated and untreated areas. Similar technologies such as the Grow Gun and previously discussed Terralift provide greater levels of soil fracturing (Smiley 2001); however, previous studies of these did not find that their probes significantly reduced bulk density or improved growth response (Smiley 2001; Smiley et al. 1990). Limitations of the Terravent™ include the absence of an accompanying method for incorporating materials such as perlite or organic matter into the soil and the limited volume of soil affected.

Air excavation is also used to achieve soil loosening in urban environments. The Air Spade® can be used to loosen or dislodge compacted soil around existing trees and can also be used in combination with organic matter and fertilizer amendments (Fite 2008).

Smiley and other researchers (Day and Bassuk 1994; Rolf 1992) have concluded that rototilling or mechanically breaking up soil prior to plant establishment and root growth, radial trenching and air excavation are more effective methods for treating soil compaction than air

injection. However, for all of these methods there is a likelihood of recompaction if subsoiled areas are exposed to heavy loads or vibration (Rolf 1994b).

Various soil amendment practices have been evaluated for either improvement of plant growth and/or soil physical properties. Studies assessing the benefits of organic matter in planting holes show a surprising lack of efficacy in improving shrub and tree growth (Corley 1984; Hummel 1985; Smalley 1995); however, Day and Bassuk (1994) suggest that this conclusion may need to be reexamined. They point out that in containers, roots are often already grown in substrates high in organic matter, making organic amendment less significant (Day et al. 1995). In support of Day and Bassuk's observation, Saebo and Ferrini's review (2006) of uses of compost for soil amendment and mulching suggests distinct benefits of compost amendment to improve soil quality during establishment of urban plants. They recommend incorporating compost to a depth of 45 cm for improved long-term tree growth. Other studies have shown that addition of organic matter improves soil structure (Albiach 2001; Diaz 1994; Pagliai 2004). Saebo and Ferrini (2006) suggest that due to the diverse organic materials tested, more research is needed to develop conclusions regarding the soil qualities and compost additives that give the best growth and health of shrub and tree species, and that general conclusions will be possible as research in this area continues.

A heavily used picnic-playground at Hains Point, D.C., was the site of a soil amendments study described by Patterson (1977). Four different amendments (sintered flyash, expanded slate, coarse construction sand, and digested sewage sludge) were compared by rotary tilling them into experimental plots. Patterson found that the soil with the 33% by volume of the expanded slate amendment had the lowest bulk density and the most pore space. Sintered fly ash

at volumes of 20% were reported to be somewhat effective and the sand and the sewage had minimal or no effect on improving the soil. Patterson concluded that all the picnic-playground area treatments produced a significant reduction in bulk density. An economical alternative to topsoil was also studied: digested sewage sludge and wood chips, urban originated leaf mould (soil composed mainly of decaying leaves) and limited topsoil. This compost helped reduce compaction, improve fertility and organic matter of urban soils (Patterson 1977).

Pittenger and Stamen (1980) evaluated the effectiveness of four soil treatment methods (135-140 power augered, angled 5-cm holes around the trunk; similarly prepared holes backfilled with 1:1 mix of sand and milled fir bark; holes prepared with a high pressure water jet; and two 10 cm holes lined with perforated PVC pipe backfilled with gravel) aimed at improving aeration and water in the surrounding soil over a two-year period. No significant differences were observed in tree growth response to the treatments during the two year period. However, under limiting moisture contents, it is unknown how these or other species would respond. Pittenger and Stamen concluded that soil moisture may be a more limiting factor in compacted soil than aeration and further that aeration treatments may not be necessary unless trees do not respond well to improved moisture conditions.

Day et al (1995) evaluated four other compaction remediation practices (peat-amended backfill; vertical drainage mat panels; radiating trenches filled with sandy loam soil; and vertical, gravel-filled sump drains) for their effect on improving high soil strength and aeration of two landscape tree species with varying tolerances to soil compaction. Treatments which alleviated compaction (soil trenches and amended backfill) increased growth of pears. Drainage mats were moderately effective. Only drainage mats and vertical drains affected aeration (*Acer* only). Day

and Bassuk concluded that efforts should be focused towards reducing mechanical impedance caused by hard soil rather than installing aeration devices.

Expanded clay and lava rock amendments for soil have also been studied for their water storage capacity and growth of 5 newly planted urban tree species (Braun 1998). Expanded clay amendment resulted in improved shoot growth especially during the second and third year for *Tilia*. The authors suggested the importance of considering the effects of aeration when planting trees in cities.

1.3 Research Objectives

Since natural recovery of compacted soils is slow (Kozlowski 1999), rehabilitation of degraded urban soil, in particular when it is severely compacted, is necessary. This study was designed to evaluate methods for improving poor soil common on urbanized land. Although this study focuses on soil conditions typical of a newly constructed building site, similar conditions persist in many urban settings and may also be exacerbated by additional construction or grey infrastructure (such as roads, sidewalks, sewers and utilities) improvements that disrupt soils. In all these cases, effective techniques for rehabilitating damaged soils with quantifiable outcomes are needed to assist arborists, landscape contractors, landscape architects, developers, and planners to prepare sites in order to achieve maximum growth for urban and landscape trees. Specifically, methods to facilitate root development in urban soils are evaluated as these are critical to achieving sufficient urban canopy cover that will yield desired benefits. Assessment of the return on rehabilitative investment in terms of tree canopy is also necessary to help achieve municipal canopy goals. The specific soil rehabilitation protocols under evaluation consist of

various levels of rehabilitative effort and include combinations of soil amendments and/or mechanical loosening techniques.

The overall objective was to determine whether damaged urban soils can be rehabilitated and whether tree establishment and growth can be improved to facilitate root development and increase canopy. The interrelationships between the rehabilitation treatments, the achieved soil physical properties, and tree establishment and growth data were used to assess the soil rehabilitation treatments and make recommendations for specific soil management techniques to optimize tree establishment and growth in urban landscape conditions.

Research Questions:

1. Can soil rehabilitative techniques be used to improve physical properties (bulk density, organic matter content, pH) of severely damaged urban soil where topsoil has been removed and subsoil compacted?

2. What level of effort of soil rehabilitation is needed to improve soil bulk density to values equal to or lower than undamaged soil conditions?

3. If achieved, can these improvements in soil physical properties improve tree growth and physiological function of trees?

4. How do these rehabilitative techniques affect rooting depth and overall number of roots?

5. How do these methods facilitate natural recovery processes such as root turnover inputs to soil organic matter content?

Chapter Two: Material and Methods

2.1 Experimental Site

The study was conducted at the Virginia Polytechnic Institute and State University's College of Agriculture's Whitethorne-Kentland (Kentland) Farm (37° 12' 1.1844", -80° 33' 48.3768"). Kentland Farm, comprised of 708 hectares of rural land, is situated adjacent to the New River in the northwestern part of Montgomery County, Virginia, and supports the research, teaching, and extension efforts of Virginia Tech. We established the Soil Rehabilitation Experimental Site (SRES) for the purposes of this study (Figure 1).

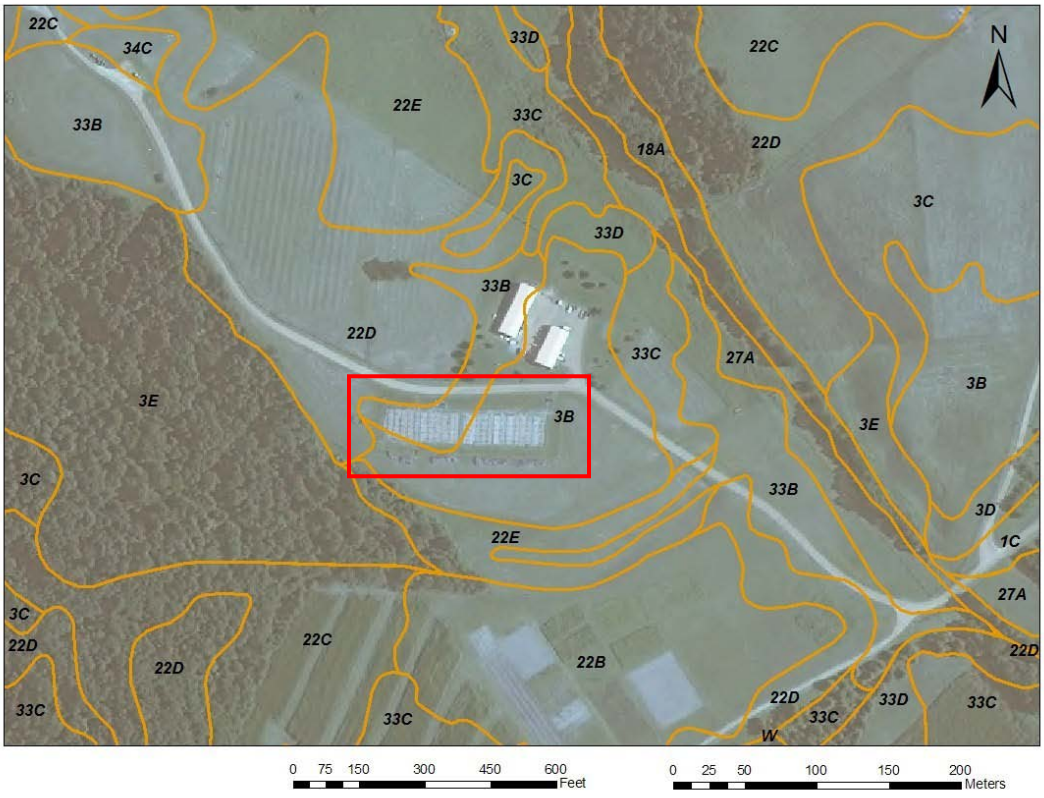

Figure 1. Location of Soil Rehabilitation Experimental Site in Kentland Farm overlain with soil series delineations (FSA National Agriculture Imagery Program 2008). Zone 3B is Shottower loam and 33B indicates Slabtown loam (Galbraith and Donovan 2005).

The SRES, installed between May 2007 and March 2008, occupies a 110 by 18 meter area oriented east to west on a slight east-facing slope (approximately 3-7 degrees) and has historically been in continual agricultural use. The soils at the SRES include Shottower loam (fine, kaolinitic, mesic Typic Paleudults) and Slabtown loam (fine-loamy, mixed, mesic Aquic Paleudalfs) (Galbraith and Donovan 2005) (Figure 1, Appendix A).

Particle size, pH, and nutrient analysis for soil from six equally distributed sampling locations along the length of the site were characterized prior to experimental site preparation by collecting surface (0 - 25.4 cm composites) and subsurface (25.4-40.6 cm deep composites) with a hand auger samples on June 13, 2007 (Table 1, Appendix B). Surface soil textures were loam and sandy loam and subsurface soil texture was a loam. Soil pH ranged between 5.3 and 6.5.

Table 1. Initial soil characterization from composite soil samples at two depths (0-25.4 cm and 25.4-40.6 cm) at six equally distributed sampling locations along the length of the SRES on June 13, 2007. See Figure 3 for plot locations.

Sample Location	Soil Series	Surface (0-25.4 cm) % sand-silt-clay	Subsurface (25.4-40.6) % sand-silt-clay
Between plots 1 and 2	Shottower	49-39-12	45-37-18
Between plots 5 and 6	Shottower	49-38-14	44-38-18
In plot 10	Shottower	54-35-11	48-38-14
Between plots 14 and 15	Slabtown	49-39-12	45-37-18
Between plots 18 and 19	Slabtown	44-45-11	44-43-13
Between plots 22 and 23	Slabtown	50-45-5	46-45-9

Soil profile descriptions from two undisturbed locations in the SRES were prepared by Dr. W. Lee Daniels of the Virginia Tech Crop and Soil Environmental Sciences (CSES) Department on October 2, 2007 (Figure 2, Appendix C). Samples collected from these profiles were analyzed to determine particle size analysis, nutrient analysis, pH and carbon-nitrogen (C/N) ratio (Appendix D). Measurements of pH in the upper 38 cm ranged from 5.5 to 6.2. Total

Figure 2. SRES soil sample Rehab #2 displayed in half-core during soil profiling (0-152 cm; top photo = upper section, middle photo = middle section, and lower photo = bottom section) prior to study installation.

soil carbon and nitrogen were determined by dry combustion using a Vario MAX CNS macro elemental analyzer (Elementar, Hanau, Germany). Nutrient analyses of both the June 2007

composite and October 2007 profile samples were performed by the Virginia Cooperative Extension Soil Testing Laboratory. Particle size analysis and C/N ratio were analyzed by the Virginia Tech soil analysis laboratories within the CSES Department. Methods used are provided in Appendix E.

Precipitation was monitored by the College of Agriculture and Life Sciences Kentland Farm's Dynamet weather station (assembled by Dynamax, Inc., Houston, TX using Campbell Scientific, Logan, UT, hardware and a model CR10X data logger) located approximately 30 meters north of the experimental plots. Precipitation was 72.7 cm in calendar year 2008 and 109.2 cm in 2009. The average annual precipitation recorded from 2004-2009 was 84.7 cm.

2.2 Experimental Plots

The experimental site, planted in grass up until installation, was divided into 24, 4.6 m × 18.3 m plots. Four soil treatments with six replications were installed in a completely randomized design (Figure 3). Approximately 0.5 m on either side of each plot was allowed as a buffer zone leaving an approximately 3.5 m width of consistent treatment area in each plot.

During treatment plot installation, water ponded at the western edge of each undisturbed plot due to the higher elevation of these plots resulting from leaving the topsoil left in place. Drains were installed in September 2007 in plot numbers 1, 3, 7, 9, 14, and 20 (Figures 4 and 5).

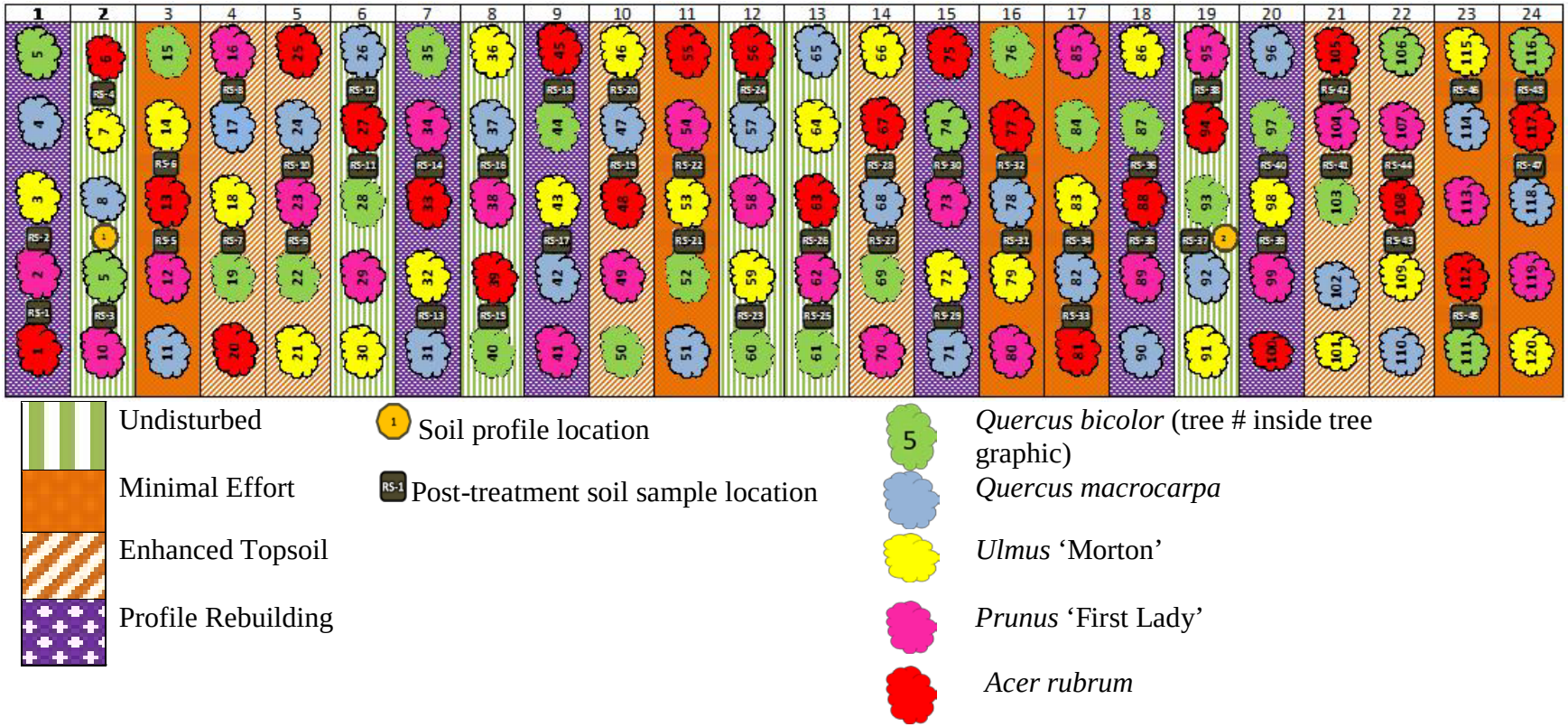

Figure 3. Soil Rehabilitation Experimental Site diagram showing a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding) with six replications installed in a completely randomized design and showing tree species and treatments. Plot 1 is on the east end of the site near road and the top of the diagram is south near the soil stockpiles.

Figure 4. Drainage ditch installation at the western edge of each undisturbed plot after pre-treatment due to the raised surface of the undisturbed topsoil.

Figure 5. Drainage ditch installation to aid in drainage created at the western edge of each undisturbed plot after pre-treatment due to the raised surface of the undisturbed topsoil.

2.3. Soil Rehabilitation Treatments

Between May and November 2007, soil treatments were applied to plots including a pre-treatment step that re-created conditions typical of newly urbanized land. Each plot was randomly assigned one of four soil treatments: undisturbed (UN), minimal effort (ME), enhanced topsoil (ET) and profile rebuilding (PR).

Pre-treatment

The UN treatment was protected from traffic during plot installation and all vegetation was killed with herbicide (glyphosate). All other plots received a pre-treatment replicating damage to soil from grading and compaction typically occurring during current land development practices common to the eastern U.S.

After plot marking and herbicide application (Figures 6 and 7), approximately 25-30 cm of the A horizon was scraped from ME, ET, and PR plots and stockpiled adjacent to the site on June 19, 2007 (Figures 8, 9, 10, 11 and 12). Following topsoil removal, during the period of July 2 to 4, 2007, the soil was hydrated to apparent field capacity (as determined by personal observation by Dr. Lee Daniels) using overhead sprinklers (Figure 13). Subsoil compaction was achieved with 8 passes of a 4,808 kilogram Ingersol Rand (Model SD45D) ride-on sheep's foot vibrating compactor (Figures 14 through 16). After pre-treatment, soil bulk density samples were collected from 3 (six locations in the first three plots) sampling locations randomly chosen in each of the 24 plots to ensure that target compaction levels for the subsoil were met (Sampling locations shown in Figure 17). Core samples were collected in removable aluminum sleeves (5 cm × 5 cm) fitted into a 5-cm diameter, 10-cm long stainless steel sampler attached to a slide

Figure 6. SRES before site marking and herbicide application

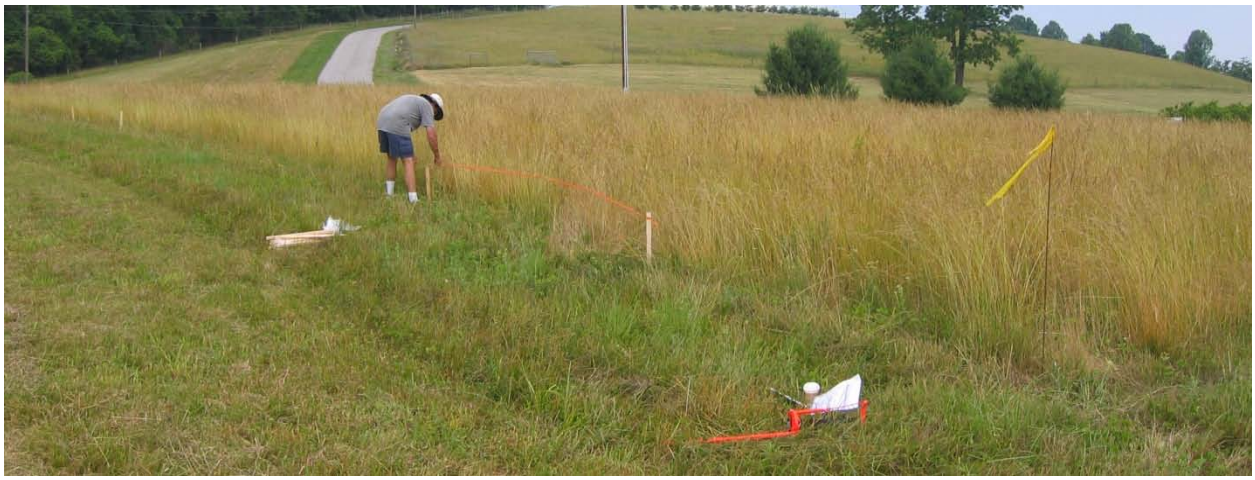

Figure 7. Marking plot dimensions on June 12, 2007.

Figure 8. SRES before scraping and compaction (June 12, 2007)

Figure 9. Scraping/stockpiling of topsoil on June 19, 2007; front loader driven by Chad Keith.

Figure 10. Scraping initial layer of topsoil with vegetation June 19, 2007.

Figure 11. Scraping 25-30 cm topsoil June 19, 2007 driven by Chad Keith.

Figure 12. After scraping and stockpiling topsoil June 28, 2007.

Figure 13. Irrigation to achieve field capacity using overhead sprinklers on July 2-4, 2007.

Figure 14. Compaction of plots on July 5, 2007, with ride-on sheep's foot vibrating compactor driven by Dr. Roger Harris.

hammer. Samples were centered at an approximate depth of 17.8 cm from the bottom of the sheep's foot impressions. Soil samples in core sleeves (90.5 cm^3) were oven-dried at 105°C to a

Figure 15. Dr. Lee Daniels confirms soil moisture for compaction on July 5, 2007.

Figure 16. After compaction on July 5, 2007.

Plot	1	3	4	5	7	9	10	11	14	15	16	17	18	20	21	22	23	24
Segment #*	T3-I	T1-I	T2-I	T2-II	T3-II	T3-III	T2-III	T1-II	T2-IV	T3-IV	T1-III	T1-IV	T3-V	T3-VI	T2-V	T2-VI	T1-V	T1-VI
1	2.01	1.87	2.07	1.87	2.00	2.05		2.03	1.79		1.93	1.95			1.79		1.99	
2	1.96	1.97	1.91				1.97			1.98		1.95	1.90	1.95		1.82		1.84
3	2.02	2.02	2.06	1.75	2.02	2.03		1.95	1.94		1.98				1.81		1.89	
4	2.02	2.09	1.96				1.95			1.95		1.96	1.87	1.87		1.81		1.82
5	2.03	1.98	1.95	2.06		1.98		1.97	1.96		1.98				1.88		1.96	
6	1.97	2.00	1.98		2.09		1.96			1.98		2.04	2.00	1.95	0.00	1.89		1.91

*Note: 1 is closest to road and 6 is closest to top soil piles.

A two-sleeve sample was used. The second sample sleeve (bottom) was used to collect the sample. The sample core with 2 sleeves was advanced into compacted soil to a little less than the height of sample core to avoid false compaction. The difficulty was that during retrieval of the sample, some of the sample fell out of the bottom (due to force needed to pull or hammer sampler back out out of ground). For the first day's samples we used a shovel to help dig out the sampler but after the rain no shovel was used.

Figure 17. Diagram indicating location of soil bulk density (g/cm^3) samples collected at the 15.2 to 20.3 cm depth after pre-treatment to characterize degree of compaction.

constant mass for determination of bulk density: Bulk Density (g/cm ^{3}) = Dry Mass (g)/Volume of Core (cm^3). The compaction process achieved a mean bulk density of 1.95 g/cm^3 (n=64, SE=0.01 g/cm^3) at approximately 5–10 cm deep (Figure 17). Bulk density in the UN plots (that received no pre-treatment) was 1.55g/cm^3 (n=6, SE=0.02 g/cm^3) at the equivalent depth.

Undisturbed (UN) Treatment

The Undisturbed (UN) treatment plots were left undisturbed except for herbicide application and provide a baseline for comparison of tree growth against tree growth in undamaged soil.

Minimum Effort (ME) Rehabilitation Treatment

The Minimum Effort (ME) treatment represents the lowest effort level of rehabilitation and represents typical practice employed by contractors to prepare a building site for landscaping. We spread 10 cm of the stockpiled topsoil over the compacted soils with a front-loading bulldozer bucket (Figure 18) and, to ensure an even spread, a tractor-pulled 10-cm box blade (scraping device) specially fabricated to ensure consistent topsoil depth (Figure 19). No mechanical loosening or organic amendment additions were performed.

Enhanced Topsoil (ET) Rehabilitation Treatment

The Enhanced Topsoil (ET) treatment represents a moderate level degree of rehabilitation. A 10 cm layer of stockpiled topsoil was spread over the treatment area in the same manner as the ME treatment plots. In addition, the plots were rototilled with a power take off (PTO) driven rototiller (Figure 20) to disturb the interface between the compacted soil and topsoil layers (Figure 21). This “scuffing of the interface” between compacted subsoil and

Figure 18. Topsoil application to ME, ET and PR plots.

Figure 19. Topsoil scraper fabricated by Jerry Stump for leveling and removing excess topsoil above 10 cm.

Figure 20. PTO driven rototiller used in ET and PR treatments at SRES.

Figure 21. Rototilling plots on November 28, 2007, by Jon Wooge.

applied topsoil is a commonly recommended practice intended to minimize the harsh transition from soil of loose density (larger soil pores and higher hydraulic conductivity) to very high density (smaller pores and lower hydraulic conductivity) thus facilitating water movement between layers (Hillel 1982).

Profile Rebuilding (PR) Rehabilitation Treatment

The Profile Rebuilding (PR) treatment involved the highest degree of rehabilitation. The PR treatment was developed for this study to rehabilitate both subsoil and topsoil and introduce organic matter deep into the profile in combination with subsoiling with the intention of facilitating deeper root growth and facilitating long-term soil improvement. The PR treatment included surface application of 10 cm of two-year-old, partially composted leaf litter in October 5, 2007 (see Chapter 3 for compost composition) (Figure 22 and 23). The leaves were collected by Virginia Tech ground crews and subjected to a windrow turner; the resulting compost was obtained from Larry Bechtel, Virginia Tech Garbage and Trash Disposal, on September 3 and 10, 2007. Compost analysis performed by A&L Analytical Laboratories, Inc. (Memphis, TN) and Virginia Tech VCE Soil Testing Laboratory is provided in Appendix F.

Compost application was followed by a subsoiling technique modified from Rolf (Rolf 1994a): a backhoe was used to penetrate to a depth of approximately 60 cm through the compost/subsoil profile; soil was lifted to approximately 2 m and allowed to fall back to ground level in order to both loosen the soil and mix the compost into the subsoil (Figure 24). Large clods were mechanically fragmented with the backhoe bucket.

Figure 22. Two-year old composted leaf litter provided by Virginia Tech grounds crew for application on PR plots on October 5, 2007.

Figure 23. Compost application to the Profile Rebuilding plots on October 5, 2007.

Figure 24. Excavating compacted soil and mixing compost into profile.

This method of subsoiling was selected because it can be employed in physically constrained urban sites (road medians, near underground infrastructure, etc.). After this subsoil treatment, 10 cm of stockpiled topsoil was applied followed by rototilling as described for the ET treatment. Subsequent sampling with a push tube confirmed that the PR treatment created veins of compost to at least 35 cm deep in the profile.

After this subsoil treatment, 10 cm of stockpiled topsoil was applied followed by rototilling as described for the ET treatment. Subsequent sampling with a push tube confirmed that the PR treatment created veins of compost to at least 35 cm deep in the profile.

Treatment Soil Characteristics

Soil physical and chemical characteristics achieved by the rehabilitation treatments were characterized approximately 8 months after treatment installation from soil samples collected in May and June 2008 (See Chapters 3 and 4). Undisturbed soil cores (5-cm D × 5-cm H) were collected at four depths (2.5-7.6 cm, 15-20 cm, 30-35 cm, and 51-56 cm) at two randomly selected midpoints between trees in each plot using a slide hammer for bulk density. Soil bulk density was calculated for each sample after oven drying at 105°C to a constant mass. Loose samples from the same depths were collected using a hand auger for other physical and chemical analysis. Samples were partially dried in the laboratory and then sieved through a 10-mesh (2 mm) screen. Particle size analysis (PSA) was determined for composites of each depth within a plot. Carbon/nitrogen ratio (C/N) was determined for each sample by dry combustion using a Vario MAX CNS macro elemental analyzer (Elementar, Hanau, Germany) Nutrient analysis including pH, and dilute acid-extractable phosphorous, potassium, calcium, magnesium, zinc, manganese, copper, iron and boron (ppm in soil) was determined by the VCE Soil Testing Laboratory.

2.4 Plant Material

Five tree species commonly used in urban settings were planted 3.7 m apart down the centerline of each plot (Figure 3 and 25). Position within the plot was randomly assigned to each species. Container-grown (26.5 L) *Acer rubrum* L. (red maple), *Quercus bicolor* Willd. (swamp white oak) and container-grown (11.4 L) *Quercus macrocarpa* Michx. (bur oak) trees were obtained from the Virginia Tech Department of Horticulture's Urban Horticulture Center nursery in Blacksburg, Virginia, USA. Container-grown trees were grown in semicomposted 100% pine

bark substrate. Bare root *Ulmus* 'Morton' (*U. japonica* (Rehd.) Sarg. × *U. wilsoniana* Schneid.) (Accolade® elm), and *Prunus* 'First Lady' (*P. xincam* × *P. campanulata*) L. (First Lady flowering cherry) were received from J. Frank Schmidt & Son Company (Boring, Oregon, USA).

Q. bicolor and *A. rubrum* trees were planted between February 28, 2008, and March 10, 2008, into planting holes of the same depth and two times the width of the root ball. Bare root trees were planted on March 17, 2008, in 70–80 cm diameter holes. *Q. macrocarpa* were planted on April 25, 2008, as replacements for another species that apparently desiccated during shipping and did not leaf out. Trees were planted in the same planting holes so as not to disturb soil treatments.

Q. bicolor trees averaged 1.14 m (SE 0.03 m) in height and 12.62 mm (SE 0.38 mm) in trunk diameter (approximately 30 cm above the root collar). *A. rubrum* trees averaged 1.82 m (SE 0.05 m) in height and 22.75 mm (SE 0.29 mm) in trunk diameter. *Q. macrocarpa* trees averaged 1.58 m (SE 0.03 m) in height and 17.21 mm (SE 0.39 mm) in trunk diameter. *U.* Morton' trees averaged 2.33 m (SE 0.03 m) in height and 20.96 mm (SE 0.31 mm) in trunk diameter. *P.* 'First Lady' trees averaged 2.00 m (SE 0.02 m) in height and 26.18 mm (SE 0.23 mm) in trunk diameter.

Trees were hand watered through the summer of 2008 during dry periods to ensure establishment. In September 2008, an irrigation system was installed and irrigation supplied periodically for the remainder of the year when trees showed water stress symptoms.

Figure 25. Container-grown and bare root tree planting.

2.5 Site Maintenance

A 0.76-mm thick, 0.6-m deep root barrier (Water Barrier/Bamboo Barrier Product #WB 24/30, Deep Root Partners, L.P., San Francisco, California) was installed between adjacent plots in an approximately 0.2-m-wide trench excavated 0.5 m deep to prevent root growth and soil movement from adjacent treatments (Figure 26). Approximately 10 cm of barrier was left exposed above ground to prevent root growth over the top of the barrier. Foot traffic was restricted to the extent possible to the buffer area after treatment installation in order to minimize compaction of treatment plots after rehabilitation.

All experimental plots were covered with SC150 double-net, straw-coconut photodegradable erosion control blankets (North American Green, Evansville, Indiana) to protect the soil from rain impact and erosion (Figure 27). Mats were secured with staples. Weeds were controlled in all plots with periodic application of glyphosate and oxyfluoren + pendimethalin. A 10-foot fence was installed around the perimeter of the plots to exclude deer.

2.6 Tree Growth and Physiological Measurements

Seasonal photographs of tree growth are provided in Appendix G.

Growth was determined by measuring tree height and trunk diameter in two perpendicular directions at 30 cm above the soil surface.

Cross-Sectional Trunk Area

Trunk cross-sectional area was calculated as $\pi D_{NS} D_{EW}/4$, where D_{NS} and D_{EW} are the two trunk diameters taken in north-south and east-west orientations. Initial readings were obtained on

Figure 26. Root barrier installation between treatment plots.

Figure 27**.** Placement of erosion control mats.

March 29, 2008, (May 9, 2008, for *Q. macrocarpa*) and end-of-year measurements were obtained December 23–26, 2008, and November 28, 2009.

Canopy Area

Canopy diameter was also measured in two perpendicular directions on March 21, 2009, and November 28, 2009, by dropping a line from the tip of the farthest reaching branches in each direction and measuring along the soil surface with a measuring tape. Canopy projection area was calculated as $\pi C_{NS}C_{EW}/4$, where C_{NS} and C_{EW} are canopy widths in the two directions. Trees were only lightly pruned on May 22, 2009, to promote future structure with the exception of the *U.* 'Morton'. Due to the possibility of wind throw, extremely vigorous shoot growth on elms was headed back and trees staked in May 2009. *U.* 'Morton' in all plots were pruned in a similar fashion.

We measured photosynthesis rate, chlorophyll fluorescence, chlorophyll content, and leaf water potential during the first two years after planting.

Photosynthesis

Photosynthesis rate was measured on one randomly chosen sun-exposed leaf from the outer canopy (3-7 nodes from twig apex) on each *A. rubrum* and *Q. bicolor* tree using a portable gas exchange analyzer (Li-6400, Li-cor Biosciences, Lincoln, Nebraska, USA) on May 27, 2008, September 13, 2008, and September 2, 2009. Settings for a CO_2 concentration of ca. 370 mmol mol^{-1} in the leaf chamber and a photosynthetically active radiation (PAR) of 1600 umol m^{-2} s^{-1} were used. Stomatal ratio was set at 0.5 for both species. Four measurements were taken on one fully expanded, sun-exposed leaf in the upper third of the southside of each tree. Measurements

were always started after attaining a steadystate of photosynthesis. IRGAs were matched before measurements were taken on each leaf.

Chlorophyll Content

Relative measurements for chlorophyll content index were made on two fully expanded, sun-exposed leaves in the upper third of the southside of each tree on July 11, 2008, September 20, 2008, and August 14, 2009 with a calibrated, hand-held, absorbance-based dual wavelength Soil Plant Analysis Development (SPAD) chlorophyll meter (Minolta SPAD 502, Spectrum Technologies, Plainfield, Illinois, USA).

Chlorophyll Fluorescence

Chlorophyll fluorescence measurements were obtained on sun-exposed leaves (one per plant) to determine maximum photochemical efficiency of photosystem II (Fv/Fm) on September 21, 2008, and August 18, 2009. Leaves were dark adapted for 20 minutes by attaching dark adapter clips to the leaf surface, avoiding the mid-vein, and chlorophyll fluorescence was measured using a "plant efficiency analyzer" (Handy PEA, Hansatech Instruments Ltd., Norfolk, England; Handy PEA software version v1.30). Measurements were recorded for 1 second with a light intensity of approximately 3000 umol m^2 s^{-1}. Measurements of Fo (initial fluorescence), Fm (maximum fluorescence) and Fv (variable fluorescence) were obtained and used to estimate the maximum quantum efficiency of photosystem II which has been shown to be proportional to the quantum yield of photochemistry and shows a high degree of correlation with the quantum yield of net photosynthesis (Baker 2008).

Leaf Water Potential

On July 19, 2008, October 1, 2008, and August 15, 2009, leaf water potential was monitored for *A. rubrum* and *Q. bicolor* by measuring leaf water potential (ψ_{leaf}) on one randomly selected leaf (3-7 nodes from twig apex) every two hours beginning at 0600 HR and ending at 2000 HR using a pressure chamber (Model 600 Pressure Chamber Instrument, PMS Instrument Co., Albany, Oregon, USA; Serial number 5417042299). After removing the leaf at the petiole, the leaf was immediately enclosed in a plastic bag and the determination of the leaf water potential was started in less than 1 min. Data were plotted for each individual replication and the area under the curve (hereafter referred to as integrated whole day water stress; I-Ψ) (Haas and Dodd 1972) was calculated using the trapezoidal rule (Zill 1985). Mean treatment pre-dawn and mid-day Ψ_{Leaf} were determined to assess treatment affects.

Root Growth

Cellulose acetate butyrate minirhizotron tubes (5-cm internal diameter and 91.5-cm length) were installed prior to tree planting between January 8 and 16, 2008, to allow non-destructive, *in situ* monitoring of *A. rubrum* and *Q. bicolor* root development and growth (Schematic and photo of minirhizotron setup is provided in Appendix H). Tubes were installed in holes on the east side of each tree beginning at the surface at a distance 91.5 cm from the center of the planting hole and advanced at 45° toward the tree with a gas powered auger followed by a hand auger to achieve the desired depth as well as minimize disturbance to soil (Bragg 1983; Johnson et al. 2001). The aboveground portion of each tube was painted black and covered with a white-painted, cut aluminum can cap to exclude moisture and light (Johnson et al. 2001). Tubes were secured with 1.27-cm diameter steel concrete reinforcement rods and wire to prevent tube movement and to allow accurate comparisons of root growth over time. Images were obtained on

July 26, 2008, December 30, 2008, June 27, 2009, and November 7, 2009. Images were collected on the uppermost surface of the minirhizotron tubes with a Bartz minirhizotron camera system (Bartz Technology Corporation, Santa Barbara, California) with an indexing handle (Johnson et al. 2001; Tingey et al. 2005). Each image frame was 1.1 cm H x 1.6 cm W (1.76 cm^2). Approximately 55 images were collected per minirhizotron tube at each sampling date. The presence of roots was determined by counting roots with diameters greater than 0.03 mm. Each replication was scored as having roots present or not present at each depth interval of 0-12 cm, 12-24 cm, 24-35 cm, 35-47 cm and 47-59 cm.

2.7 Statistical Analysis

Analyses of variance (ANOVA) and mean comparisons by protected ($P<0.1$) least significance difference (LSD) were determined using JMP, version 8.0 (SAS Institute Inc., Cary, North Carolina, USA) at the $\alpha=0.05$ significance level.

Treatment comparisons for the presence or absence of roots against minirhizotron observation panels were made with single-degree-of-freedom contrasts within the Genmod procedure of SAS, version 9.2 (SAS Institute Inc. Cary, North Carolina) utilizing the logit link within SAS (Schabenberger and Pierce 2002).

Chapter Three: Comparison of Site Preparation Methods for Severely Damaged Urban Soil: Effects on Soil Properties and Tree Root Development of *Acer rubrum* L. and *Quercus bicolor* Willd.

Abstract

Sustained urban tree growth and canopy development depend on adequate root penetration of soil to acquire sufficient nutrients and water. This process is limited when topsoil is removed and soil is compacted, such as where common construction activities associated with urban land development remove organic matter and damage existing soil structure. Effective soil improvement methods which enhance root development and growth and provide quantifiable results are therefore needed. Typical post-urban-development soil repair practices as well as more intensive methods for restoring graded and compacted soil were evaluated for their effect on soil physical properties and root distribution for two urban tree species. Four soil preparation methods were evaluated: minimum effort (ME) (topsoil replacement only); enhanced topsoil (ET) (topsoil replacement and rototilling); profile rebuilding (PR) (compost amendment, subsoiling to 60 cm depth, topsoil replacement, and rototilling); and undisturbed (UN) (representing pre-urbanization soil condition) as control plots. All plots except UN were pretreated by removing A-horizon soil and compacting subsoil to an average bulk density of 1.95 g/cm^3, replicating typical urban land development practices. A single, angled minirhizotron tube for non-destructive, *in situ* root observation was installed on each of 6 replications of each *Acer rubrum* L. (red maple) and *Quercus bicolor* Willd. (swamp white oak) trees. Treatment effects on the presence or absence of roots one and two years after transplanting were evaluated through

minirhizotron observation panels at five depth intervals (0-12 cm, 12-24 cm, 24-35 cm, 35-47 cm and 47-59 cm). Eight months after treatment preparation, no treatment effects on surface soil density were present. In contrast, bulk density at the soil depth severely compacted by pre-treatment (15–20 cm) was significantly lower in only the PR treatment (1.34 g/cm^3) compared to 1.8 g/cm^3 in the ME and ET treatments, where pre-treated subsoil was not mechanically loosened and 1.51 g/cm^3 at the corresponding depth in the UN plots. C/N ratio and pH were increased by the compost addition in the PR treatments.

Although root presence was less prevalent in zones of highest soil compaction (approximately 10-25 cm depth), *A. rubrum* roots were observed at all depths in the ET, ME and PR treatment after two growing seasons and were observed in 33% or more of the minirhizotron tubes at all depths in the PR treatment. For *Quercus bicolor* trees, roots were only observed in the top 12 cm of soil in ME plots, while only trees in PR and UN plots had roots present at 35 cm or deeper. *Q. bicolor* roots were only observed at all depths in the UN treatment. Future monitoring will be necessary to determine long-term treatment effects on root growth and depth and on root turnover and organic inputs into the soil profiles. Overall, these results suggest that the soil improvement methods associated with greater levels of rehabilitative effort are capable of reducing soil bulk density, increasing fertility and organic matter content. These methods have the potential to improve aeration, nutrient and water availability, permeability, and minimize mechanical impedance for optimal root growth in loam soil.

Keywords: soil compaction, urban soil, bulk density, organic amendments, compost, root depth

3.1 Introduction

Urban tree canopy cover is desirable in urban communities for its diverse environmental, social and economic benefits. Removal of trees during land development directly reduces canopy cover, and healthy, urban trees face numerous challenges during their establishment and growth towards replacement of this canopy. Challenges include limited root and canopy space; deficient or excess water, excess light and heat; air or soil pollution; mechanical and chemical damage; and lack of adequate funding for proper management or maintenance. Poor soil quality, however, is frequently reported as the greatest limiting factor for optimal tree survival and growth (Craul 1992; De Kimpe and Morel 2000; Huinink 1998; Jim 1998; Karlen et al. 1997; Pouyat 2007; Scharenbroch et al. 2005; Schindelbeck et al. 2008; Vrscaj et al. 2008). During urbanization, construction activities remove natural topsoil and severely compact remaining soil (Randrup and Dralle 1997; Short et al. 1986).

Compacted soil with limited organic matter impairs the ability of roots to penetrate the soil to acquire nutrients, oxygen and water and subsequently impairs optimal tree growth and canopy development. Aboveground and belowground plant litter are primary sources of organic matter in the soil (Kögel-Knabner 2002). Such natural organic matter inputs can be limited in urban environments because aboveground organic matter inputs (i.e., leaves and plant debris) may be removed (Sæbø and Ferrini 2006) and belowground organic matter inputs (i.e., root litter and rhizodeposition) are reduced if root development and penetration into the soil matrix is restricted by soil compaction.

Organic matter is a necessary component of soil for the development of soil structure and it aids in sustaining water and nutrient supplies (Powers et al. 2005; Powers et al. 1990; Rivenshield and Bassuk 2007). While the relationship between organic inputs over time and soil structure stability (aggregate stability) are not clear (Abiven et al 2008), it has been demonstrated that humates resulting from organic matter decomposition improve soil structure and facilitate root exploration into larger volumes of soil for nutrient and water uptake (Piccolo and Mbagwu 1999). Compost amendments, in particular, may also supply nutrients and aid in improved water storage capacity of soil. Some authors have recommended 5% as a target organic matter content for urban soils (Sæbø and Ferrini 2006), but many factors such as existing soil quality, planned management and the plants used must be considered. Scharenbroch et al (2005) concluded in their review of the physical, chemical and biological properties distinguishing older and newer urban soil that of all the soil forming factors, time played the most significant role reducing the impacts of urbanization through natural processes. Organic matter was greater in older urban soils compared to newer ones.

Urban soil compaction also has adverse impacts on soil's ability to support ecosystems in and around cities (Pavao-Zuckerman 2008). Grading during building construction frequently compacts urban soils. When water content is low, compacted soils can be extremely strong and impenetrable, and when soil is too wet, inadequate aeration can result. Soil structure and pore function are altered and both the movement of water/solute, nutrients and gases in the soil are hindered, restricting the penetration of root tips through the soil (Day et al. 2000; Greacen and Sands 1980; Horn et al. 1995; Kozlowski 1999; Patterson 1977; Paul W. Adams and Froehlich 1981; Taylor and Brar 1991; Taylor et al. 1966). Alleviating soil compaction is therefore

desirable to improve tree growth and longevity. Although numerous approaches to relieving soil compaction to improve tree growth have been studied, none has successfully addressed subsoil compaction in urban settings.

Despite current knowledge regarding requirements for rooting, soil improvement to enhance long-term tree growth is not widely practiced in urban land development. Effective techniques for rehabilitating damaged soils with quantifiable outcomes are needed to assist arborists, landscape contractors, landscape architects, developers, and planners to provide maximum growth for urban and landscape trees. In addition, the new voluntary certification standards for sustainable sites codified by the Sustainable Sites Initiative (SITES^{TM}) requires soil restoration for soil damaged during the construction process. Thus, careful evaluation of soil rehabilitation methods is needed to determine their impacts on soil physical, chemical, and biological properties as well as the ability to support plant growth and provide other ecosystem services.

The current study is the initial phase of a long-term soil rehabilitation experiment to evaluate the effects of several soil rehabilitation protocols on physical and chemical properties of soil, root growth of trees, and their interactions. The North American long-term soil productivity study, targeting the effects of forest management on soil porosity and site organic matter, showed that complete removal of surface organic matter leads to declines in soil C to a depth of 20 cm after 10 years and that growth appeared to be reduced by compaction on clayey soils and increased on sandy soils (Powers et al. 2005). Our objectives were to determine whether urban soil damaged by land development practices can be improved and how this soil rehabilitation

affects soil properties as well as initial root growth and distribution in the soil profile. This study evaluates the effects of varying levels of effort that combine topsoil replacement, the addition of organic matter amendments, and mechanical loosening. Typical urban land development practices result in a zone of extremely compacted subsoil. We hypothesized that a rehabilitation treatment that directly targets this compacted zone through a subsoiling technique and introduces organic matter at depth will enable enhanced root penetration into lower soil layers and result in improved soil physical characteristics. The SRES made it possible to assess the effects of the soil treatments without potential interactions of other factors (soil contamination, limited canopy or rooting space, etc.) that can also challenge urban tree establishment and growth.

3.2 Materials and Methods

See Chapter 2 for complete site and treatment descriptions.

Experimental Site

The study was carried out at Virginia Tech's Whitethorne-Kentland Research Farm (37° 12' 1.1844" N, 80° 33' 48.3768" W) near Blacksburg, Virginia. Two loam soils, Shottower loam (fine, kaolinitic, mesic Typic Paleudults) and Slabtown loam (fine-loamy, mixed, mesic Aquic Paleudalfs) (Galbraith and Donovan 2005), are present at the site. The experimental site is oriented east to west on a slight east-facing slope (approximately 3–7°) and has historically been in agricultural use. The site had been planted in pasture grass for at least 12-15 years before installation of the experiment.

Site Preparation and Experimental Design

Between May 2007 and November 2007, 24 4.6 ×18.3 m adjacent plots (6 replications × 4 soil treatments) were prepared in a completely randomized experimental design. Each plot was randomly assigned one of four soil treatments: undisturbed (UN), minimal effort (ME), enhanced topsoil (ET), and profile rebuilding (PR).

Pre-Treatment

The UN treatment plots were protected from traffic during plot installation and all vegetation was killed with glyphosate herbicide. All other plots received a pre-treatment common to current land development practices in the Eastern United States. Approximately 25–30 cm of the A horizon was scraped and stockpiled adjacent to the site on June 19, 2007. Following topsoil removal, subsoil was compacted with eight passes of a 4,800 kg sheep's foot vibrating riding compactor to a mean bulk density of 1.95 g/cm^3 (n=64, SE=0.01 g/cm^3) at approximately 5–10 cm deep.

Rehabilitation Treatments

Soil rehabilitation protocols under evaluation represent low-to-high levels of rehabilitative effort in ME, ET, and PR plots, respectively. The ME treatment represents typical practice employed by contractors to prepare a building site for landscaping. ME included surface application of approximately 10 cm of the stockpiled topsoil onto the compacted subsoil. We used a tractor-pulled box blade (scraping device) specially fabricated to ensure consistent topsoil depth. The ET treatment was prepared similar to the ME treatment except a rototiller was used to disturb the interface between the compacted soil and topsoil layers after topsoil application. This

"scuffing of the interface" between topsoil and subsoil is sometimes recommended to enhance water movement and plant growth. The PR treatment was developed for this study to rehabilitate both subsoil and topsoil and introduce organic matter deep into the profile in combination with subsoiling with the intention of facilitating deeper root growth and facilitating long-term soil improvement. The PR treatment included surface application of 10 cm of two-year-old, partially composted leaf litter (mostly deciduous hardwood trees) (see Table 2 for composition). Compost application was followed by a subsoiling technique modified from Rolf (Rolf 1994a): a backhoe was used to penetrate to a depth of approximately 60 cm through the compost/subsoil profile; soil was lifted to approximately 2 m and allowed to fall back to ground level in order to both loosen the soil and mix the compost into the subsoil. Large clods were mechanically fragmented with the backhoe bucket. This method of subsoiling was selected because it can be employed in physically constrained urban sites (road medians, near underground infrastructure, etc.). After this subsoil treatment, 10 cm of stockpiled topsoil was applied followed by rototilling as described for the ET treatment. Subsequent sampling with a push tube and observation through minirhizotron tubes confirmed that the PR treatment created veins of compost to at least 35 cm deep in the profile.

A 0.76-mm thick, 0.6-m deep root barrier (Water Barrier/Bamboo Barrier Product #WB 24/30, Deep Root Partners, L.P., San Francisco, California) was installed between adjacent plots in an approximately 0.2-m-wide trench excavated 0.5 m deep to prevent root growth and soil movement from adjacent treatments. Approximately 10 cm of barrier was left exposed above ground to prevent root growth over the top of the barrier. All plots were covered with straw

erosion control blankets to protect soil from rain impact and erosion. Weeds were controlled in all plots with periodic application of glyphosate and oxyfluoren + pendimethalin.

Plant Material

Saplings of two tree species commonly used in urban settings were randomly planted in two of five locations 3.7 m apart down the centerline of each plot. The remaining locations were planted with other species not included in this study. Container-grown (26.5 L) *Acer rubrum* L. and *Quercus bicolor* Willd. were obtained from the Virginia Tech Department of Horticulture's Urban Horticulture Center nursery in Blacksburg, Virginia, USA. The trees were grown in semicomposted 100% pine bark substrate. *Q. bicolor* and *A. rubrum* trees were planted between February 28, 2008, and March 10, 2008, into planting holes of the same depth as the root ball and two times the width of the root ball.

Characterization of Soil after Treatment Installation

The soil physical and chemical characteristics achieved by the rehabilitation treatments were characterized approximately 8 months after treatment installation from soil samples collected in May and June 2008 (Table 2, Figure 28). Undisturbed soil cores (5-cm D × 5-cm H) were collected at four depths (2.5-7.6 cm, 15.2-20.3 cm, 30.5-35.5 cm, 50.8-55.9 cm) at two randomly selected midpoints between trees in each plot using a slide hammer. Soil bulk density was calculated for each sample after oven drying at 105°C to a constant weight. Particle size analysis (PSA) was determined for composites of each depth within a plot. Carbon/nitrogen ratio (C/N) was determined for each sample by dry combustion using a Vario MAX CNS macro

Table 2. Mean soil bulk density, pH and C/N ratio for samples collected at four depths (2.5-7.6 cm, 15.2-20.3 cm, 30.5-35.5 cm, 50.8-55.9 cm) in a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding) in May through June of 2008. (n=6)

	Depth (cm)			
	2.5 -7.6	15.2-20.3	30.5-35.5	50.8-55.9
Treatment		Bulk Density (g/cm^3) [x]		
UN	1.52 (0.04)	1.51 (0.14) ab	1.55 (0.15)	1.62 (0.08)
ME	1.39 (0.13)	1.76 (0.17) a	1.76 (0.02)	1.77 (0.03)
ET	1.39 (0.06)	1.84 (0.04) a	1.69 (0.03)	1.76 (0.01)
PR	1.28 (0.03)	1.34 (0.05) b	1.68 (0.06)	1.75 (0.01)
	pH [y, v]			
UN	5.3 (0.1) b	5.7 (0.1) b	5.7 (0.2) b	5.1 (0.1)
ME	5.5 (0.1) b	5.6 (0.1) b	5.3 (0.1) c	5.4 (0.2)
ET	5.4 (0.1) b	5.8 (0.1) b	5.6 (0.1) bc	5.6 (0.5)
PR	6.3 (0.3) a	7.1 (0.1) a	6.6 (0.2) a	5.1 (0.02)
	C/N Ratio [w, u]			
UN	10.0 (0.17) b	10.3 (0.22) b	8.1 (0.30) b	8.2 (0.70) a
ME	10.2 (0.24) b	10.1 (0.29) b	8.1 (0.47) b	6.3 (0.50) ab
ET	10.0 (0.13) b	9.7 (0.23) b	8.4 (0.39) b	5.1 (1.58) b
PR	12.3 (0.54) a	14.9 (0.32) a	13.4 (0.71) a	8.3 (0.65) a

[z] Treatment means followed by the same letter within a depth (as shown in table columns) are not significantly different at the α=0.05 level (comparisonwise), using mean comparison by protected (P<0.1) LSD

[y] Numbers in parentheses indicate standard errors of the mean

[x] n = 6 with 2 subsamples

[w] n = 6 with composite of 2 subsamples

[v] Composted leaf litter pH: 7.3 (A&L Laboratories), 7.4 and 7.6 (VCE Soil Testing Lab)

[u] Composted leaf litter C/N ratio (3 subsamples): 15.0

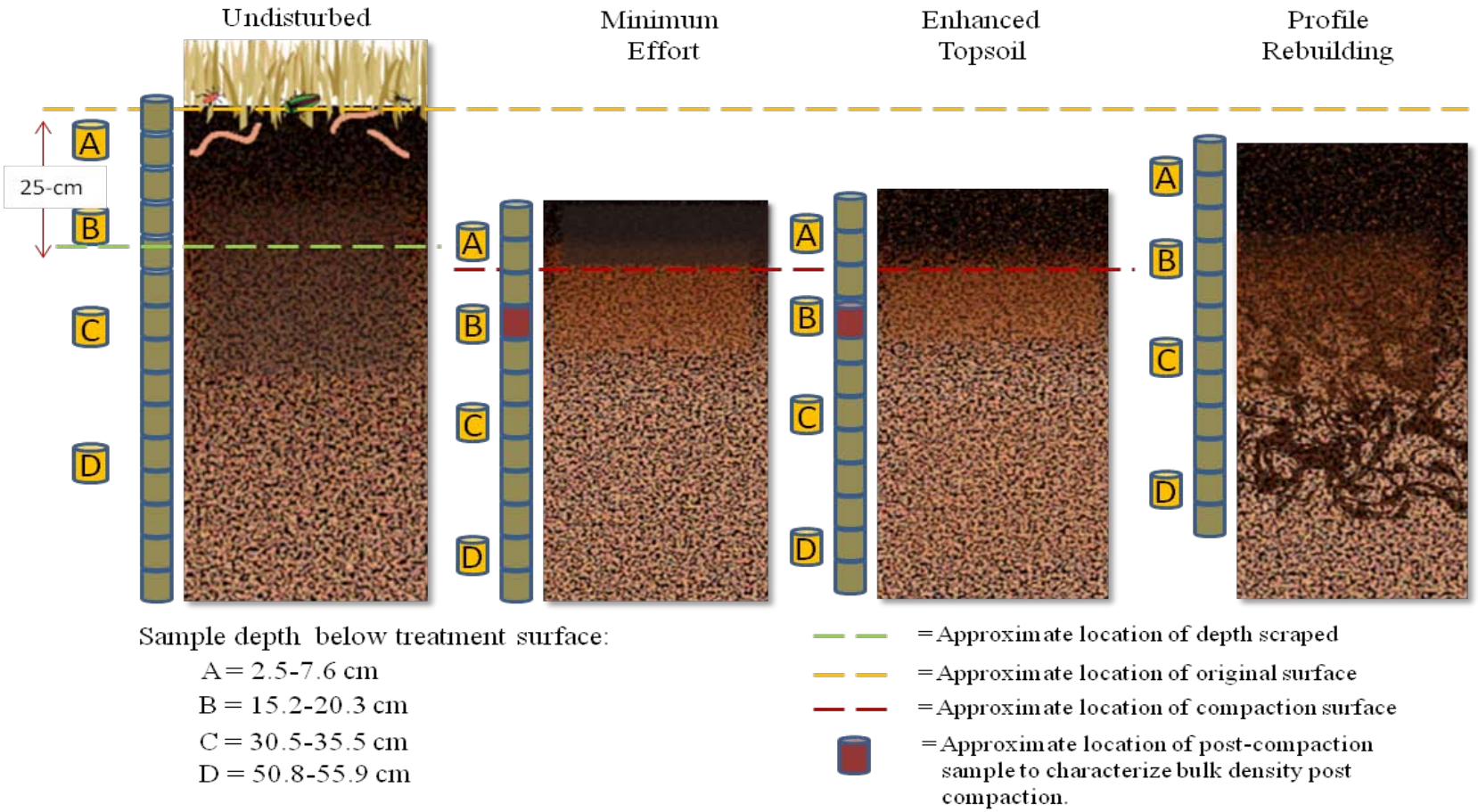

Figure 28**.** Approximation of sample depth comparison for pre-treatment compacted layer among the control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding). (Adopted from Sarah Gugercin/Day figure - not to scale)

elemental analyzer (Elementar, Hanau, Germany). Composted leaf litter nutrient and C/N ratio analyses were performed by A&L Analytical Laboratories Inc. (Memphis, Tennessee, USA) and Virginia Tech's Virginia Cooperative Extension Soil Testing Laboratory, respectively.

Root Growth Measurements

Cellulose acetate butyrate minirhizotron tubes (5-cm internal diameter and 91.5-cm length) were installed prior to tree planting between January 8 and 16, 2008, to allow non-destructive, *in situ* monitoring of *A. rubrum* and *Q. bicolor* root development and growth. Tubes were installed in holes on the east side of each tree beginning at the surface at a distance 91.5 cm from the center of the planting hole and advanced at 45° toward the tree with a gas powered auger followed by a hand auger to achieve the desired depth as well as minimize disturbance to soil (Johnson et al, 2001). The aboveground portion of each tube was painted black and covered with a white-painted, aluminum cap to exclude moisture and light (Johnson et al. 2001). Tubes were secured with 1.3-cm diameter steel concrete reinforcement rods and wire to prevent tube movement and to allow accurate comparisons of root growth over time. Images were obtained on July 26, 2008, December 30, 2008, June 27, 2009, and November 7, 2009 from the uppermost surface of the minirhizotron tubes with a Bartz minirhizotron camera system (Bartz Technology Corporation, Santa Barbara, California) with an indexing handle (Johnson et al. 2001; Tingey et al. 2005). Each image frame was 1.1 cm H x 1.6 cm W (1.76 cm^2). Approximately 55 images were collected per minirhizotron tube at each sampling date. The presence of roots was determined by counting roots with diameters greater than 3 mm. Each replication was scored as having roots present or not present at each depth interval of 0-12 cm, 12-24 cm, 24-35 cm, 35-47 cm and 47-59 cm.

3.3 Statistical Analysis

Analyses of variance (ANOVA) and mean comparisons by protected ($p<0.1$) least significance difference (LSD) were determined using JMP, version 8.0 (SAS Institute Inc., Cary, North Carolina, USA) at the $\alpha=0.05$ significance level. Treatment comparisons for the presence or absence of roots against minirhizotron observation panels were analyzed with single-degree-of-freedom contrasts within the Genmod procedure of SAS, version 9.2 (SAS Institute Inc. Cary, North Carolina) utilizing the logit link within SAS (Schabenberger and Pierce 2002).

3.4 Results and Discussion

Soil Characterization

In the upper (2.5-7.5 cm deep) layer, no effect on bulk density could be attributed to treatments after 8 months (Table 2, Figure 28). Scraping, removal and replacement of topsoil onto the ME, ET and PR treatments may have "fluffed" up their topsoil, whereas the UN topsoil was undisturbed and did not receive topsoil mechanical loosening.

In contrast, treatment effects on bulk density were most pronounced just below the added topsoil layer (15-20 cm deep), where the PR plots had lower density than in plots of lower rehabilitative effort (ME, ET) (Table 2). As expected, the subsoiling and organic amendments had a significant loosening effect on the zone of extremely compacted subsoil as evidenced by a mean bulk density of 1.34 g/cm^3. The PR treatment reduced the bulk density of the compacted layer to below values considered to be root- limiting (1.4 g/cm^3 to 1.6 g/cm^3) for fine textured loam soils (Daddow and Warrington 1983; Kozlowski 1999; Zisa et al. 1980). In this zone, bulk density was 1.8 g/cm^3 for ME and ET treatments, where subsoil had been compacted by the pre-

treatment but was not mechanically loosened. The ET treatment rototilling component was intended to mechanically loosen the compacted layer but due to the high bulk density it had a limited effect on the compacted layer. The "scuffing" of the interface in the ET would not likely have reduced the compacted in this layer. The undisturbed plots (UN) that did not receive the severe pre-treatment compaction had marginally lower bulk density. The combination of the mechanical loosening through subsoiling and integration of the composted leaf litter with rototilling reduced PR soil bulk density by 24 % and 27 % less than that of the ME and ET treatments, respectively, and this reduction persisted for at least 8 months.

Treatment effects on bulk density were not evident at the deeper depths (30 cm and below), where pre-treatment compaction had less effect and remediation potentially did not reach intended depths of 56 cm. Due to the potential lack of homogeneity throughout the PR treatment soil from the subsoiling process, it is also possible that PR bulk density could be higher if one or more of the analyzed samples originated from a compacted "clod" redistributed to a deeper depth during subsoiling. Bulk density and pH were not affected by the mechanical loosening and organic amendment in the 51–56 cm depth. This is likely explained by the subsoiling component of the treatment installation not fully penetrating to the planned 60 cm depth in all locations or compost not being evenly distributed at all depths from its original location at the subsoil surface.

Soil pH was slightly acid (5.1-5.8) for all treatments at all depths except for the PR treatment (Table 2). Soil pH was increased at all depths in the PR treatments except 51-56 cm. This increase was the expected result of treatment (subsoiling and rototilling) of these plots with

leaf litter compost, which had a higher pH (7.3 to 7.6) than the subsoil before incorporation of organic matter. To some extent the elevated pH at the 30-35 cm depth may also be a result of ion leaching from soil layers above. These higher pH levels (7.06) in the 15-20 deep layer of the PR plots would probably not affect the health of most trees, but could be problematic for certain species and might be alleviated with acidulating amendments.

With the exception of the PR treatment, C/N ratios in each treatment (Table 2) generally decreased with depth. C/N ratios ranged from 5.1 to 10.3 in the UN, ME, and ET treatments; C/N ratio ranged from 8.3 to 14.9 in the PR treatment. The greater mean C/N ratios in the PR treatment are likely a result of the leaf litter compost amendment (C/N ratio of 15.0) and suggest that efforts to incorporate organic matter at depth were successful.

Soil texture was consistent throughout. As expected with these soil series, particle size analyses reveal predominantly loam soil texture at all depths sampled in all treatments (Table 3), with clay loam observed beneath 20 cm in some plots. Treatment differences observed in mean mineral concentrations (P, K, Ca, Mg, Zn, Mn, and B), CEC, acidity and base saturation (Table 4) in the PR treatment are believed to be associated with the compost incorporation in the PR treatment. The PR treatment increased fertility in the PR treatment in the upper 35 cm.

Root Growth

Few roots were only observed in the UN and PR treatment minirhizotron images in 2008. Root presence was still limited after the second growing season, indicating that we were able to capture the initial period of root exploration. After two growing seasons, roots were still only present in a small proportion of minirhizotron frames, but root distribution patterns were

Table 3. Mean particle size percentages and standard error (in parentheses) including textural class for samples collected at four depths (2.5-7.6 cm, 15.2-20.3 cm, 30.5-35.5 cm, 50.8-55.9 cm) in a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding) 8 months after treatment installation. (n=6)

	% Sand [Z]	% Silt [Z]	% Clay [Z]	Textural Class
2.5 -7.6 cm depth				
UN	48 (0.8)	40 (1.3)	12 (1.3)	Loam
ME	47 (0.9)	43 (1.2)	10 (0.3)	Loam
ET	48 (0.4)	40 (0.8)	12 (0.5)	Loam
PR	48 (0.5)	39 (1.5)	13 (1.4)	Loam
15.2-20.3 cm depth				
UN	46 (0.6)	40 (1.4)	14 (1.5)	Loam
ME	46 (0.5)	40 (0.8)	14 (1.0)	Loam
ET	46 (0.3)	39 (1.1)	15 (1.3)	Loam
PR	46 (1.3)	39 (1.4)	15 (1.5)	Loam
30.5-35.5 cm depth				
UN	44 (0.5)	37 (1.4)	19 (1.5)	Loam
ME	42 (1.2)	37 (1.4)	21 (2.2)	Loam
ET	44 (0.8)	35 (1.5)	21 (2.3)	Loam/Clay Loam
PR	45 (0.8)	37 (0.9)	18 (1.4)	Loam
50.8-55.9 cm depth				
UN	43 (1.4)	34 (1.6)	23 (2.7)	Loam
ME	41 (1.0)	32 (1.6)	27 (2.1)	Clay Loam/Loam
ET	45 (3.4)	36 (1.2)	19 (4.5)	Loam
PR	43 (0.9)	36 (1.6)	21 (2.4)	Loam

[Z] Composite of 2 subsamples analyzed for each plot replicate at each depth

Table 4. Chemical properties for soil samples collected at four depths in a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding) 8 months after treatment installation. (n=6)

	Depth (cm)			
	2.5-7.6	15.2-20.3	30.5-35.5	50.8-55.9
Treatment	Phosphorous (P) ppm in soil (mg/kg) [z,y,x]			
UN	3.2 (0.4) b	2.5 (0.2)	2.5 (0.3)	2.0 (0.0)
ME	3.3 (0.6) b	2.0 (0.0)	2.0 (0.0)	2.0 (0.0)
ET	5.8 (2.6) a b	29.6 (27.4)	23.9 (21.9)	2.0 (0.0)
PR	7.8 (1.4) a	10.5 (1.5)	4.8 (0.8)	2.0 (0.0)
	Potassium (K) ppm in soil (mg/kg) [z,y,x]			
UN	99.5 (7.92) a b	73.1 (8.14) b	71.2 (8.19) b	44.0 (13.32)
ME	87.8 (7.20) b	67.3 (4.73) b	68.9 (7.33) b	65.3 (31.32)
ET	89.2 (4.68) b	84.5 (17.05) b	90.3 (21.20) b	79.0 (26.00)
PR	112.9 (11.34) a	149.2 (12.70) a	124.8 (11.1) a	54.0 (15.72)
	Calcium (Ca) ppm in soil (mg/kg) [z,y,x]			
UN	380.9 (25.6) b	312.9 (24.7) b	282.6 (23.3) b	248.6 (41.3)
ME	361.4 (13.2) b	268.4 (4.4) b	244.1 (13.9) b	332.6 (24.0)
ET	362.8 (10.1) b	327.9 (31.2) b	313.4 (33.0) b	258.0 (55.0)
PR	798.7 (141.9) a	1333.2 (144.7) a	791.1 (88.5) a	321.3 (82.0)
	Magnesium (Mg) ppm in soil (mg/kg) [z,y,x]			
UN	86.8 (6.00) b	73.6 (7.55) b	98.7 (11.22) b	96.0 (10.6)
ME	82.0 (6.38) b	77.9 (7.25) b	108.3 (10.2) b	123.7 (11.3)
ET	81.0 (4.80) b	82.1 (9.80) b	107.9 (15.8) b	114.5 (13.5)
PR	154.2 (24.4) a	235.2 (26.3) a	175.0 (13.4) a	118.3 (13.9)
	Zinc (Zn) ppm in soil (mg/kg) [z,y,x]			
UN	0.89 (0.07) b	0.50 (0.013) b	0.38 (0.09) b	0.30 (0.10)
ME	0.93 (0.09) b	0.43 (0.017) b	0.27 (0.02) b	0.20 (0.0)
ET	0.83 (0.08) b	0.49 (0.066) b	0.33 (0.02) b	0.25 (0.05)
PR	1.61 (0.38) a	2.12 (0.238) a	1.12 (0.14) a	0.47 (0.09)
	Manganese (Mn) ppm in soil (mg/kg) [z,y,x]			
UN	9.6 (0.82) b	10.2 (2.24) b	4.9 (0.693) b	4.5 (1.048) b
ME	12.9 (1.72) ab	8.8 (0.915) b	4.5 (0.604) b	1.9 (0.696) c
ET	10.0 (0.46) b	7.7 (0.823) b	4.5 (0.793) b	2.8 (0.800) bc
PR	15.0 (2.72) a	25.6 (1.96) a	16.2 (2.14) a	7.0 (0.203) a

Table 4. Continued

Treatment	Depth (cm) 2.5-7.6	15.2-20.3	30.5-35.5	50.8-55.9
	Copper (Cu) ppm in soil (mg/kg) [z,y,x]			
UN	0.31 (0.06)	0.33 (0.08)	0.31 (0.06)	0.40 (0.10)
ME	0.36 (0.07)	0.37 (0.07)	0.31 (0.06)	0.23 (0.03)
ET	0.44 (0.06)	0.40 (0.06)	0.38 (0.05)	0.20 (0.00)
PR	0.34 (0.04)	0.30 (0.05)	0.33 (0.05)	0.40 (0.12)
	Iron (Fe) ppm in soil (mg/kg) [z,y,x]			
UN	8.43 (0.74)	8.75 (0.54)	9.750 (0.76)	9.90 (0.90)
ME	9.29 (0.46)	9.53 (0.37)	10.13 (0.33)	10.90 (1.46)
ET	8.93 (0.58)	9.77 (1.21)	9.100 (0.48)	9.55 (1.35)
PR	8.25 (0.27)	9.22 (0.45)	10.31 (0.57)	10.33 (0.48)
	Boron (B) ppm in soil (mg/kg) [z,y,x]			
UN	0.24 (0.02) b	0.19 (0.01) b	0.14 (0.02) b	0.17 (0.03)
ME	0.26 (0.02) b	0.19 (0.01) b	0.17 (0.02) b	0.17 (0.03)
ET	0.23 (0.02) b	0.18 (0.01) b	0.18 (0.01) b	0.15 (0.05)
PR	0.67 (0.15) a	1.32 (0.15) a	0.78 (0.11) a	0.23 (0.09)
	Estimated Cation Exchange Capacity (CEC) meq/100g soil [z,y,x]			
UN	4.16 (0.19) b	3.23 (0.09) b	3.11 (0.20) b	3.97 (0.39)
ME	4.00 (0.14) b	2.76 (0.07) b	3.40 (0.37) b	4.17 (0.60)
ET	4.08 (0.10) b	3.18 (0.26) b	3.33 (0.33) b	3.45 (1.25)
PR	5.99 (0.76) a	9.00 (0.94) a	5.83 (0.53) a	4.23 (0.95)
	Acidity (%) [z,y,x]			
UN	31.0 (4.6) a	26.2 (5.7)	21.0 (5.8) a	45.4 (6.8)
ME	32.7 (2.7) a	21.1 (2.9)	28.6 (4.7) a	27.9 (14.0)
ET	33.4 (2.1) a	19.3 (5.0)	19.6 (2.0) ab	21.8 (19.9)
PR	10.2 (5.0) b	3.9 (3.2)	8.3 (4.8) b	35.1 (1.9)
	Base Saturation (%) [z,y,x]			
UN	69.1 (4.7) b	73.8 (5.7) b	79.0 (5.8) b	54.6 (6.8)
ME	67.3 (2.7) b	78.9 (2.9) b	71.4 (4.7) b	72.1 (14.0)
ET	66.6 (2.1) b	80.7 (5.0) b	80.4 (2.0) b	78.3 (19.9)
PR	89.9 (5.0) a	99.4 (0.6) a	96.4 (2.0) a	64.9 (1.9)

Table 4. Continued

Treatment	Depth (cm) 2.5-7.6	15.2-20.3	30.5-35.5	50.8-55.9
		Ca Saturation (%) [z,y,x]		
UN	45.6 (3.2) b	49.2 (3.9) b	46.5 (3.5) bc	31.3 (4.3)
ME	44.9 (1.6) b	49.2 (1.6) b	38.4 (3.1) c	41.7 (6.7)
ET	44.5 (0.8) b	51.6 (1.1) b	47.3 (2.0) b	40.1 (6.9)
PR	64.0 (4.2) a	73.5 (0.6) a	65.3 (2.7) a	37.5 (1.7)
		Mg Saturation (%) [z,y,x]		
UN	17.3 (1.6) b	18.9 (2.0)	26.6 (2.9)	20.6 (3.6)
ME	16.8 (1.2) b	23.4 (2.0)	27.6 (1.8)	25.7 (4.9)
ET	16.5 (1.2) b	22.4 (3.8)	26.5 (2.6)	30.5 (8.2)
PR	20.8 (1.0) a	21.4 (0.3)	25.4 (1.8)	24.3 (3.2)
		K Saturation (%) [z,y,x]		
UN	6.2 (0.5)	5.7 (0.5) ab	5.9 (0.6)	2.7 (0.7)
ME	5.6 (0.4)	6.2 (0.4) a	5.5 (0.7)	4.8 (3.0)
ET	5.6 (0.4)	6.7 (1.0) a	6.6 (1.0)	7.7 (4.8)
PR	5.0 (0.2)	4.4 (0.3) b	5.8 (0.2)	3.1 (0.5)

[z] Treatment means followed by the same letter within a depth (as shown in table columns) are not significantly different at the α=0.05 level (comparisonwise), using mean comparison by protected ($p<0.10$) LSD

[y] Numbers in parentheses indicate standard errors of the mean

[x] n = 6 with 2 subsamples (except n = 2 or 3 at 50.8-55.9 cm depth)

becoming evident. While roots were present at all depth intervals to 59 cm below ground surface after two years, definitive treatment effects on rooting depth will likely become more evident in the future (Table 5, Figure 29). After two growing seasons, *A. rubrum* roots were observed at all depth intervals in the ET, ME and PR treatments. Roots were observed at all depths in 33% or more of the *A. rubrum* tubes in the PR treatment. Root presence was observed at greater percentage of tubes in the upper 25 cm of the ET and PR treatments. *A. rubrum* roots are known

Table 5. Treatment comparisons for probabilities of the presence of roots on minirhizotrons at different soil depths for *Acer rubrum* L. (red maple) and *Quercus bicolor* Willd. (swamp white oak) trees. n=6. See Figure 29 for percentages of replications with visible roots at each depth.

	Soil depth (cm)					
	0-12	12-24	24-35	35-47	47-59	Entire Tube
Acer rubrum	P > ChiSq					
ET vs. ME[z]	0.016	1.000	0.213	0.213	0.213	0.005
ET vs. PR	0.213	0.016	1.000	0.557	1.000	0.796
ET vs. UN	0.213	0.502	0.213	0.557	0.023	0.062
ME vs. PR	0.213	0.016	0.213	0.502	0.213	0.002
PR vs. UN	1.000	0.071	0.213	1.000	0.023	0.034
ME vs. UN	0.213	0.502	1.000	0.502	0.224	0.345
Quercus bicolor						
ET vs. ME	0.075	1.000	0.224	1.000	X[y]	0.550
ET vs. PR	0.224	1.000	0.224	0.075	X	0.290
ET vs. UN	0.006	0.224	1.000	0.075	X	0.001
ME vs. PR	0.502	1.000	1.000	0.075	X	0.639
PR vs. UN	0.071	0.224	0.224	1.000	X	0.025
ME vs. UN	0.244	0.224	0.224	1.000	X	0.007

[z] ET = enhanced topsoil; PR = profile rebuilding; UN = uncompacted; ME = minimum effort (ME).

[y] Uniform effects resulted in a negative of the Hessian matrix that was not positive definite. The contrasts were therefore not estimable.

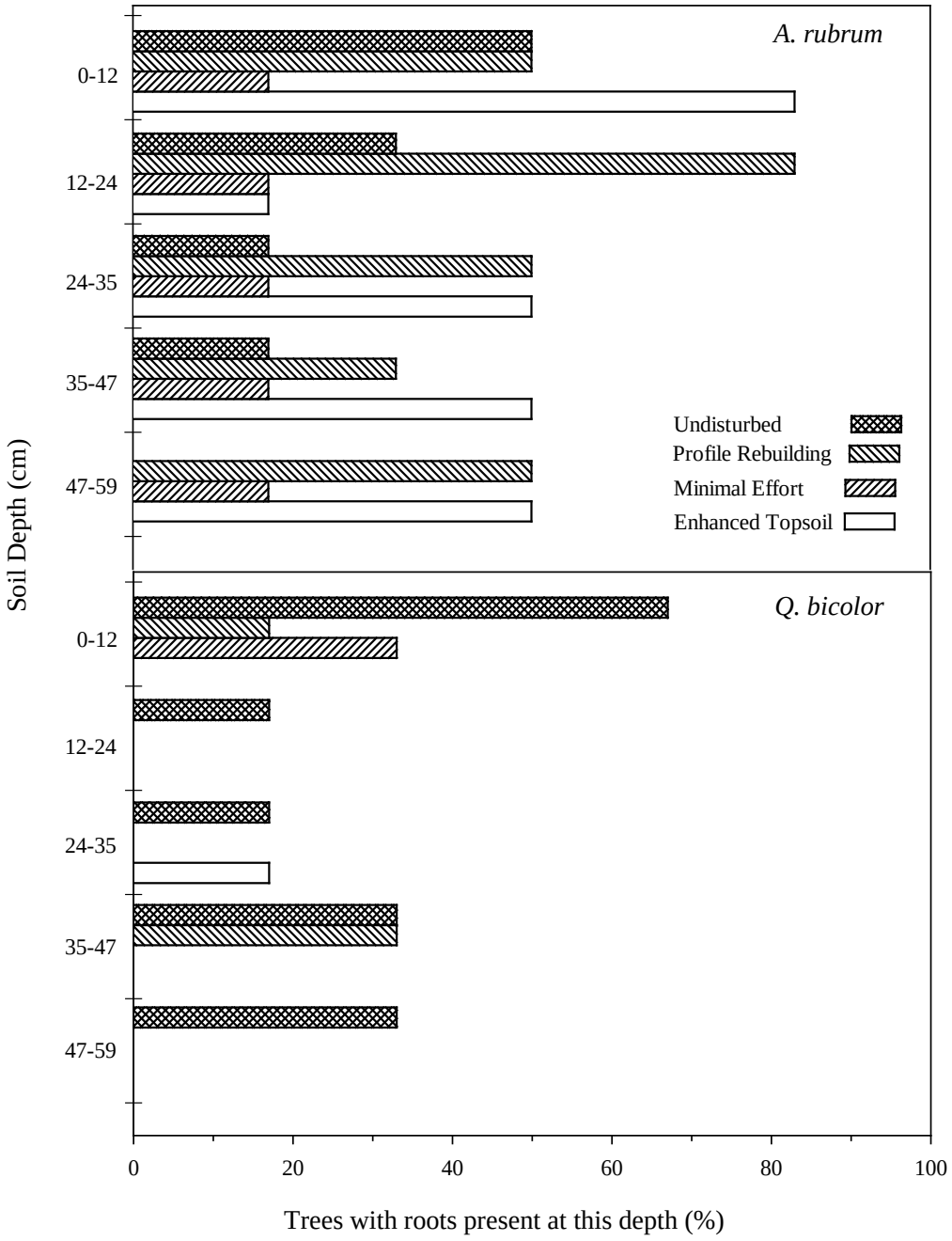

Figure 29. Percentage of replicates of *Acer rubrum* L. and *Quercus bicolor* Willd. trees with visible roots observed in minirhizotron tube images at five soil depths (0-12 cm, 12-24 cm, 24-35 cm, 35-47 cm and 47-59 cm) after two (2009) years of growth in a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding). (n=6)

for their horizontal form and presence in the upper 25 cm (10 in) of soil (Walters and Yawney 1990). *Q. bicolor* roots were observed at all depths in the UN treatment. *Q. bicolor* is known for its slow initial growth and shallow rooting system.

Penetration of roots in the ME and ET treatments into the depth of pre-treatment compaction (15.3-20.3 cm) as shown in Figure 29 was not expected. Soil compaction is known to restrict root growth as soil is compressed and macroporosity is decreased and soil strength is increased (Daddow and Warrington 1983; Day et al. 2010b). It is not clear at this time whether the planting holes aided root penetration through the compacted layers. We believe that the limited root data obtained after the second year growing season after transplanting may be related to the both the greater distance of the minirhizotron tube from the tree relative to the expected root system diameter present and the small sampling area resulting from a single tube per tree.

3.5 Conclusion

Overall, these results suggest that the soil improvement methods associated with greater levels of rehabilitative effort are capable of reducing soil bulk density and increasing organic matter content and fertility and that these effects can persist for at least 8 months after installation. These methods have the potential to improve aeration, nutrient and water availability, permeability, and minimize mechanical impedance for optimal root growth in loam soil. We conclude that soil rehabilitation via the PR treatment can improve soil physical conditions compared to the typical soil preparation methods by both mechanically loosening the compacted soil and integrating organic matter amendments into the surface and subsoil. Reduced soil bulk density was achieved in the pre-treated layer where growth limiting bulk density values

were measured. Increases in C/N ratios and fertility in the PR treatment indicated that organic matter amendments were successfully incorporated into the subsoil layers and we believe this will aid in natural soil building processes as organic matter is decomposed. The PR rehabilitation method is intended to facilitate natural profile rebuilding processes for urban environments, where organic inputs can be limited. Veins of compost observed deep in the soil profile minirhizotron frames in the PR treatment after two years suggest this process has begun.

Treatment effect on rooting depth after two years varied by species. Greater root presence was observed in deeper soil layers of ET and PR treatments for *A. rubrum* and of UN and PR for *Q. bicolor;* root distribution was not measured for other species. Roots were observed, but not expected, in the compacted subsoil layer of ME treatment; it is possible the planting holes served as a conduit for the roots to penetrate this layer. Additionally, minirhizotron measurements only capture a small proportion of the root system, and measurement variability is high. Nonetheless, there was evidence that soil compaction restricted root penetration in both species, and that, for Q. bicolor, root exploration of deeper soil layers was restricted in soil subjected to typical soil preparation practices, represented by the ME and ET treatments.

As tree canopies increase and root volume increases, placing greater demands water and nutrient reserves in the soil, treatment effects on root growth can be better assessed in the future. Additionally, soil moisture data will provide valuable data regarding plant and treatment soil-water relationships. Species variation in growth rate and environmental tolerance also appeared to influence early growth treatment effects. Future monitoring of soil and roots will be necessary to determine long-term treatment effects on root growth and depth as well as treatment effects on root turnover and organic inputs into the soil profiles. Additionally, this experiment took place on two closely related loamy soil series and findings may be applicable only to similarly textured

soils and tree species. Fine sandy soils, for example, are more resistant to compaction and may be expected to respond differently.

Chapter Four: Effects of Soil Rehabilitation Methods for Severely Compacted Soil on Growth and Physiological Response of Five Urban Tree Species

Abstract

Construction activities that accompany urban land development damage soil structure, remove organic matter, and contribute to poor tree survival and growth. Effective soil improvement methods are needed to improve the growth and canopy development of landscape trees. Typical practice and improved methods for restoring graded and compacted soil were evaluated for their effect on physiological response and growth of five urban tree species. Six replications each of four soil treatments were randomly assigned to 24 plots: minimum effort (ME) (topsoil replacement only); enhanced topsoil (ET) (topsoil replacement and rototilling); profile rebuilding (PR) (compost amendment, subsoiling to 60 cm depth, topsoil replacement, and rototilling); and undisturbed (UN) (no grading, scraping or improvement methods employed) as the control plots. All plots except UN were pretreated by removing A horizon soil, grading, and compacting subsoil to an average bulk density of 1.95 g/cm^3, mimicking typical land development practices. Growth and physiology were evaluated over 2 years for: *Acer rubrum* (red maple), *Quercus bicolor* (swamp white oak), *Ulmus* 'Morton' (Accolade® elm), *Prunus* 'First Lady' (*P. xincam* ×*P. campanulata*) (First Lady flowering cherry), and *Quercus macrocarpa* (bur oak). In the 15–20 cm depth (zone of original compacted subsoil), bulk density was only reduced in the PR treatment. At this depth, the PR treatment reduced the mean bulk density (1.34 g/cm^3) to 24 % and 27 % less than that of the ME and ET treatments, respectively. C/N ratio and pH were increased by the compost addition in the PR treatments. Tree survival was 100% for all species and treatments. First year mean canopy spread for *U.* 'Morton' was

383% greater in the PR treatment than the ME treatment. At the end of two years, mean canopy areas of *A. rubrum, U.* 'Morton' and *Q. macrocarpa* was greater in the PR plots than in ME plots. The only observed difference in mean canopy area between the ET and ME plots after the second year was for *Q. macrocarpa*. Second-year tree growth was greater in the PR treatment for all species. Cross-sectional trunk area ranged from 16% to 71% greater in the PR plots than in ME plots. *Q. bicolor* photosynthesis rates in the PR treatment were greater than all other treatments for both years.

We conclude that more intensive soil rehabilitation via PR treatment can improve soil conditions and accelerate the establishment and growth of some species compared to the typical soil preparation methods in the first two years. Future monitoring of soil and tree growth will help determine more conclusive long-term treatment effects on growth and physiological response and canopy .

Keywords: bulk density, compost, organic amendments, soil compaction, urban soil

4.1 Introduction

Green spaces and tree canopy have become integral components of urban infrastructure and sustainable community environments. For centuries, urban trees have been recognized for their social and economic benefits, and healthy urban trees that provide adequate canopy cover have become vital tools for improving and restoring urban environmental quality (Nowak et al. 2001). Urban trees mitigate stormwater through canopy capture (Xiao and McPherson 2002; Xiao et al. 2000) and improved soil infiltration (Bartens 2008; Bramley 2003), improve air quality, reduce noise, improve aesthetics, moderate temperature (McPherson 2001) and provide habitats for birds and other animals (Matthews 2010). However, urban tree survival and growth rates are often poor, and the tree canopy necessary to provide these environmental and social benefits is often not achieved (Whitlow et al. 1992).

Soil quality requirements for urban environments have become the subject of much research and poor soil quality is frequently reported as the greatest limiting factor for optimal tree survival and growth (De Kimpe and Morel 2000; Huinink 1998; Jim 1998; Karlen et al. 1997; Pouyat 2007; Scharenbroch et al. 2005; Schindelbeck et al. 2008; Vrscaj et al. 2008). In Pavao-Zuckerman's discussion of the nature and role of urban soils in ecological restoration (2008), both the direct disturbance and altering of soil development processes as well as unique features of the urban environment are described as major factors affecting urban soils. Specifically, construction activities associated with urban development severely compact urban soil and remove organic matter (Randrup and Dralle 1997). Poor tree survival and establishment, slow growth rates and reduced tree canopy coverage often occur. Adverse effects of soil compaction on the growth and yield of woody plants have been both a concern and subject of research for many years (Kozlowski 1999). Soil compaction increases bulk density and has been

shown to severely limit root growth and reduce urban tree survival (Day et al. 2000). Soil compaction alters soil structure and pore function, hindering the movement of water/solute, nutrients and gases in the soil, and the penetration of root tips through the soil (Day et al. 2000; Greacen and Sands 1980; Horn et al. 1995; Kozlowski 1999; Patterson 1977; Paul W. Adams and Froehlich 1981). Organic matter is removed during construction activities when topsoil is removed from the development site. Organic matter is necessary for the development of soil structure and aids in sustaining water and nutrient supplies (Hillel 1982; Powers et al. 1990).

Scientific evidence is lacking to inform specifications for soil improvement that can be used in local ordinances and site-development protocols. Many municipalities rely on canopy cover stipulations in local ordinances to maintain or increase community tree canopy cover. Increasingly tree canopy is being employed to meet regulatory requirements concerning water and air quality. Thus it is increasingly important for environmental planning purposes that municipalities can estimate anticipated canopy cover from a given tree planting. Currently there are few or no canopy estimation procedures that include any soil information. Consequently, estimations are frequently highly inaccurate (McPherson 2001), and developers who employ improved soil protection and rehabilitation practices do not receive credit (in terms of anticipating greater tree canopy) for their efforts. Effective techniques for rehabilitating damaged soils and providing quantifiable results in terms of tree canopy are therefore needed to assist arborists, landscape contractors, landscape architects, developers, and planners to provide maximum growth for urban and landscape trees. As transition from rural to developed urban land and economic redevelopment (brownfield restoration, revitalization of towns and cities, etc.) continues (Macie and Hermansen 2002), such degraded soil conditions will also continue to be an important focus of urban planners and developers (Pavao-Zuckerman 2008). The new

voluntary certification standards for sustainable sites, codified by the Sustainable Sites Initiative (SITES^{TM}) (Sustainable Sites Initiative: Guidelines and Performance Benchmarks 2009. Available at http://www.sustainablesites.org/report) requires restoration of soil degraded during the construction process. In summary, soil improvement methods to aid optimal tree canopy development are needed as an essential tool for achieving urban canopy goals and predicting canopy growth response to rehabilitated soil. Measurement of the return on rehabilitative investment in terms of tree canopy is also essential in order for municipalities and developers to ensure that they meet their canopy goals both sustainably and efficiently.

The current study is the initial phase of a long-term soil rehabilitation experiment to evaluate several soil rehabilitation protocols in terms of their effects on tree establishment and growth and on soil properties. Our objectives were to determine whether soil damaged by typical land development practices can be rehabilitated and how this soil rehabilitation affects tree establishment and growth. We hypothesized that greater levels of rehabilitative effort will result in greater reductions in soil bulk density and increases in tree growth, canopy development, and physiological vigor.

4.2 Materials and Methods

See Chapter 2 for complete site and treatment descriptions.

Experimental Site

The study was carried out at Virginia Tech's Whitethorne-Kentland Research Farm (37° 12' 1.1844" N, 80° 33' 48.3768" W) near Blacksburg, Virginia. Two loam soils, Shottower loam (fine, kaolinitic, mesic Typic Paleudults) and Slabtown loam (fine-loamy, mixed, mesic Aquic Paleudalfs) (Galbraith 2005) are present at the site. The experimental site is oriented east to west

on a slight east-facing slope (approximately 3–7°) and has historically been in agricultural use. The site had been planted in pasture grass for cover for 12-15 years until initiation of the experiment.

Site Preparation and Experimental Design

Between May 2007 and November 2007, 24 4.6 ×18.3 m adjacent plots (6 replications × 4 soil treatments) were prepared in a completely randomized experimental design. Each plot was randomly assigned one of four soil treatments: undisturbed (UN), minimal effort (ME), enhanced topsoil (ET), and profile rebuilding (PR).

Pre-Treatment

The UN treatment plots were protected from traffic during plot preparation and all vegetation was killed with glyphosate herbicide. All other plots received a pre-treatment common to current land development practices in the Eastern United States. Approximately 25–30 cm of the A horizon was scraped and stockpiled adjacent to the site on June 19, 2007. Following topsoil removal, subsoil was compacted with eight passes of a 4,800 kg sheep's foot vibrating riding compactor to a mean bulk density of 1.95 g/cm^3 (n=64, SE=0.01 g/cm^3) at approximately 5–10 cm deep.

Rehabilitation Treatments

Soil rehabilitation protocols under evaluation represent low-to-high levels of rehabilitative effort in ME, ET, and PR plots, respectively. The ME treatment represents typical practice employed by contractors to prepare a building site for landscaping. ME included surface application of approximately 10 cm of the stockpiled topsoil onto the compacted subsoil. We used a tractor-pulled box blade (scraping device) specially fabricated to ensure consistent topsoil

depth. The ET treatment was the same as the ME treatment except that after topsoil was applied, a rototiller was used to disturb the interface between the compacted soil and topsoil layers. This "scuffing of the interface" between topsoil and subsoil is sometimes recommended to enhance water movement and plant growth.

The PR treatment was developed for this study to rehabilitate both topsoil and subsoil with the intention of facilitating deeper root growth and facilitating long-term soil improvement. This treatment included surface application of 10 cm of two-year-old, partially composted leaf litter (mostly deciduous hardwood trees) in October 2007 (see Table 2 for composition). Compost application was followed by a subsoiling technique modified from Rolf (1994a): a backhoe was used to penetrate to a depth of approximately 60 cm through the compost/subsoil profile; soil was lifted to approximately 2 m and allowed to fall back to ground level in order to both loosen the soil and mix the compost into the subsoil. Large clods were mechanically fragmented with the backhoe bucket. This method of subsoiling was selected because it can be employed in physically constrained urban sites (road medians, near underground infrastructure, etc.). After this subsoil treatment, 10 cm of stockpiled topsoil was applied followed by rototilling as described for the ET treatment. Subsequent sampling with a push tube confirmed that the PR treatment created veins of compost to at least 35 cm deep in the profile.

A 0.76-mm thick, 0.6-m deep root barrier (Water Barrier/Bamboo Barrier Product #WB 24/30, Deep Root Partners, L.P., San Francisco, California) was installed between adjacent plots in an approximately 0.2-m-wide trench excavated 0.5 m deep to prevent root growth and soil movement from adjacent treatments. Approximately 10 cm of barrier was left exposed above ground to prevent root growth over the top of the barrier. All plots were covered with straw

erosion control blankets to protect soil from rain impact and erosion. Weeds were controlled in all plots with periodic application of glyphosate and oxyfluoren + pendimethalin.

Plant Material

Saplings of five tree species commonly used in urban settings were planted 3.7 m apart down the centerline of each plot. Position within the plot was randomly assigned to each species. Container-grown (26.5 L) *Acer rubrum* L., *Quercus bicolor* Willd. and container-grown (11.4 L) *Quercus macrocarpa* Michx. trees were obtained from the Virginia Tech Department of Horticulture's Urban Horticulture Center nursery in Blacksburg, Virginia, USA. Container-grown trees were grown in semicomposted 100% pine bark substrate. Bare root *Ulmus* 'Morton' (Accolade®) (*U. japonica* (Rehd.) Sarg. × *U. wilsoniana* Schneid.) and *Prunus* 'First Lady' (*P. xincam* × *P. campanulata*) L. were received from J. Frank Schmidt & Son Company (Boring, Oregon, USA).

Q. bicolor and *A. rubrum* trees were planted between February 28, 2008, and March 10, 2008, into planting holes of the same depth and two times the width of the root ball. Bare root trees were planted on March 17, 2008, in 70–80 cm diameter holes. *Q. macrocarpa* were planted on April 25, 2008, as replacements for another species that apparently desiccated during shipping and did not leaf out. Trees were planted in the same planting holes so as not to disturb soil treatments.

Characterization of Soil After Site Preparation

The soil physical and chemical characteristics achieved by the rehabilitation treatments were characterized approximately one year after site preparation from soil samples conducted in May and June 2008. Undisturbed soil cores (5-cm D × 5-cm H) were collected at four depths at

two randomly selected midpoints between trees in each plot using a slide hammer. Soil bulk density was calculated for each sample after oven drying at 105°C to a constant weight. Particle size analysis (PSA) was determined for composites of each depth within a plot. Carbon/nitrogen ratio (C/N) was determined for each sample by dry combustion using a Vario MAX CNS macro elemental analyzer (Elementar, Hanau, Germany). Composted leaf litter nutrient and C/N ratio analyses were performed by A&L Analytical Laboratories Inc. (Memphis, Tennessee, USA) and Virginia Tech's Virginia Cooperative Extension Soil Testing Laboratory, respectively.

Growth Measurements

Growth was determined by measuring tree height and trunk diameter in two perpendicular directions at 30 cm above the soil surface. Trunk cross-sectional area was calculated as $\pi D_{NS} D_{EW}/4$, where D_{NS} and D_{EW} are the two trunk diameters. Initial readings were obtained on March 29, 2008, (May 9, 2008, for *Q. macrocarpa*) and end-of-year measurements were obtained December 23–26, 2008, and November 28, 2009. Canopy diameter was also measured in two perpendicular directions on March 21, 2009, and November 28, 2009, by dropping a line from the tip of the farthest reaching branches in each direction and measuring along the soil surface with a measuring tape. Canopy projection area was calculated as $\pi C_{NS} C_{EW}/4$, where C_{NS} and C_{EW} are canopy widths in the two directions. Trees were only lightly pruned on May 22, 2009, to promote future structure with the exception of the *U.* 'Morton'. Due to the possibility of wind throw, extremely vigorous shoot growth on elms had to be headed back and trees staked in May 2009. *U.* 'Morton' in all plots were pruned in a similar fashion.

Physiological Measurements

We measured photosynthesis rate, chlorophyll fluorescence, chlorophyll content, and leaf water potential during the first two years after planting. Photosynthesis rate was measured on one

randomly chosen sun-exposed leaf from the outer canopy (3-7 nodes from twig apex) on each A. rubrum and Q. bicolor tree using a portable gas exchange analyzer (Li-6400, Li-cor Biosciences, Lincoln, Nebraska, USA) on May 27, 2008, September 13, 2008, and September 2, 2009. Measurements for chlorophyll content index were made on two similarly selected sun-exposed leaves per tree using a colorimetric meter (Minolta SPAD 502, Spectrum Technologies, Plainfield, Illinois, USA) on July 11, 2008, September 20, 2008, and August 14, 2009. Chlorophyll fluorescence measurements were obtained after sun-exposed leaves (one per plant) were dark-adapted for 20 min prior to measurement of the maximum photochemical efficiency of photosystem II (Fv/Fm) on September 21, 2008, and August 18, 2009. On July 19, 2008, October 1, 2008, and August 15, 2009, leaf water potential was monitored for *A. rubrum* and *Q. bicolor* by measuring leaf water potential (ψleaf) on one randomly selected leaf (3-7 nodes from twig apex) every two hours beginning at 0600 HR and ending at 2000 HR using a pressure chamber (Model 600 Pressure Chamber Instrument, PMS Instrument Co., Albany, Oregon, USA). Data were plotted for each individual replication and the area under the curve (hereafter referred to as integrated whole day water stress; I-Ψ) was calculated using the trapezoidal rule (Zill 1985).

Statistical Analysis

Analyses of variance (ANOVA) and mean comparisons by protected ($P<0.1$) least significance difference (LSD) were determined using JMP, version 8.0 (SAS Institute Inc., Cary, North Carolina, USA) at the $\alpha = 0.05$ significance level. Species were analyzed separately.

4.3 Results and Discussion

Soil Characterization

In the upper (2.5-7.6 cm deep) soil layer, no significant treatment effects on bulk density were observed one year after treatment preparation (Table 2 in Chapter 3). Bulk density of the undisturbed plots (UN) in the upper layer was somewhat higher than the other treatments. Scraping, removal and replacement of topsoil onto the ME, ET and PR treatments may have "fluffed" up the topsoil, whereas the UN topsoil was undisturbed and did not receive topsoil mechanical loosening.

Treatment effects on bulk density were most pronounced just below the added topsoil layer (15-20 cm deep), where the maximum effort plots (PR) had lower density than plots of lower rehabilitative effort (ME, ET) (Table 2). The undisturbed plots (UN) that did not receive the severe pre-treatment compaction had marginally lower bulk density, while the combination of the mechanical loosening through subsoiling and integration of the composted leaf litter with rototilling in the PR treatment most likely reduced the bulk density of the compacted layer.

Treatment effects on bulk density were not evident at the lower depths evaluated (30-35 cm and 51-56 cm deep). Treatment effects were expected at the 30.5-35.5 depth due to subsoiling, which incorporated organic matter to this depth as indicated by the pH and C/N ratio results (Table 2).

Soil pH was slightly acid (5.1-5.8) for all treatments at all depths except for the PR treatment (Table 2). Soil pH was increased in the PR treatments at all depths except 51-56 cm. This increase was the expected result of treatment of these plots with compost which had a pH range of 7.3 to 7.6 before incorporation. To some extent the elevated pH at the 30-35 cm depth

may be a result of ion leaching from soil layers above. The high pH levels (7.06) in the 15-20 deep layers of the PR plots would probably not affect the health of most trees.

The PR treatment successfully incorporated compost into the soil profile to a depth of 35 cm as indicated by increased C/N ratio at all depths except the 51-56 depth (Table 2) At the 51–56 cm depth, bulk density, C/N ratio and pH were not as affected by the mechanical loosening and organic amendment. This lack of effect may be explained by possible failure of subsoiling to fully penetrate to the planned 60 cm depth in all locations (Figure 28).

Overall, these results suggest that the PR treatment can improve soil physical and chemical properties to depth of 35 cm in the first year after treatment, while the commonly employed ME and ET treatments, as expected, had little or no effect on soil properties in the top 10 cm.

Tree Growth

Excluding the initial planting that failed to leaf out after transplanting and was replaced with *Q. macrocarpa*, survival was 100%.

U. 'Morton' is known for its rapid establishment (Dirr 1998) and perhaps for this reason showed the most pronounced treatment response one and two years after planting. Annual height growth was significantly greater for the PR treatment of *U.* 'Morton,' with a respective annual height increase of 135% in 2008 when compared to the ME treatment, which most closely replicates standard practice (Table 6). A lower percent increase (46%) observed in 2009 may partly be a response to the pruning performed in Spring 2009 on this species.

U. 'Morton' canopy area in the PR treatment was at least 250% greater than all other treatments in the first-year (2008) post-transplant season (Figure 30). The first year after

Table 6. Mean tree height increase (m) and standard error (in parentheses) for *Acer rubrum* L., *Quercus bicolor* Willd., *Ulmus* 'Morton' (Accolade®) (*Ulmus japonica* (Rehd.) Sarg. x *Ulmus wilsoniana* Schneid.), *Prunus* 'First Lady' (*Prunus xincam* x *Prunus campanulata*) L. and *Quercus macrocarpa* Michx. trees growing in a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding) for the first (2008) and second (2009) growing seasons. n=6.

	Height increase (m) [z]	
	2008	2009
Acer rubrum		
UN	0.46 (0.12)	0.90 (0.07)
ME	0.68 (0.12)	0.78 (0.08)
ET	0.64 (0.16)	0.93 (0.12)
PR	0.78 (0.19)	0.88 (0.13)
Quercus bicolor		
UN	0.16 (0.04)	0.49 (0.08)
ME	0.21 (0.04)	0.52 (0.08)
ET	0.19 (0.06)	0.50 (0.07)
PR	0.18 (0.04)	0.53 (0.06)
Ulmus 'Morton'		
UN	0.50 (0.20) b	1.10 (0.17)
ME	0.55 (0.20) b	0.97 (0.13)
ET	0.48 (0.28) b	0.96 (0.15)
PR	1.29 (0.23) a	1.42 (0.16)
Prunus 'First Lady'		
UN	0.24 (0.03)	0.49 (0.12)
ME	0.32 (0.05)	0.48 (0.12)
ET	0.25 (0.02)	0.62 (0.11)
PR	0.29 (0.03)	0.74 (0.12)
Quercus macrocarpa		
UN	0.08 (0.03)	0.76 (0.10)
ME	0.06 (0.02)	0.80 (0.14)
ET	0.06 (0.04)	0.92 (0.12)
PR	0.08 (0.03)	1.10 (0.08)

[z] Means followed by the same letter within a species are not significantly different at the α=0.05 level (comparisonwise), using mean comparison by protected (P<0.1) LSD.

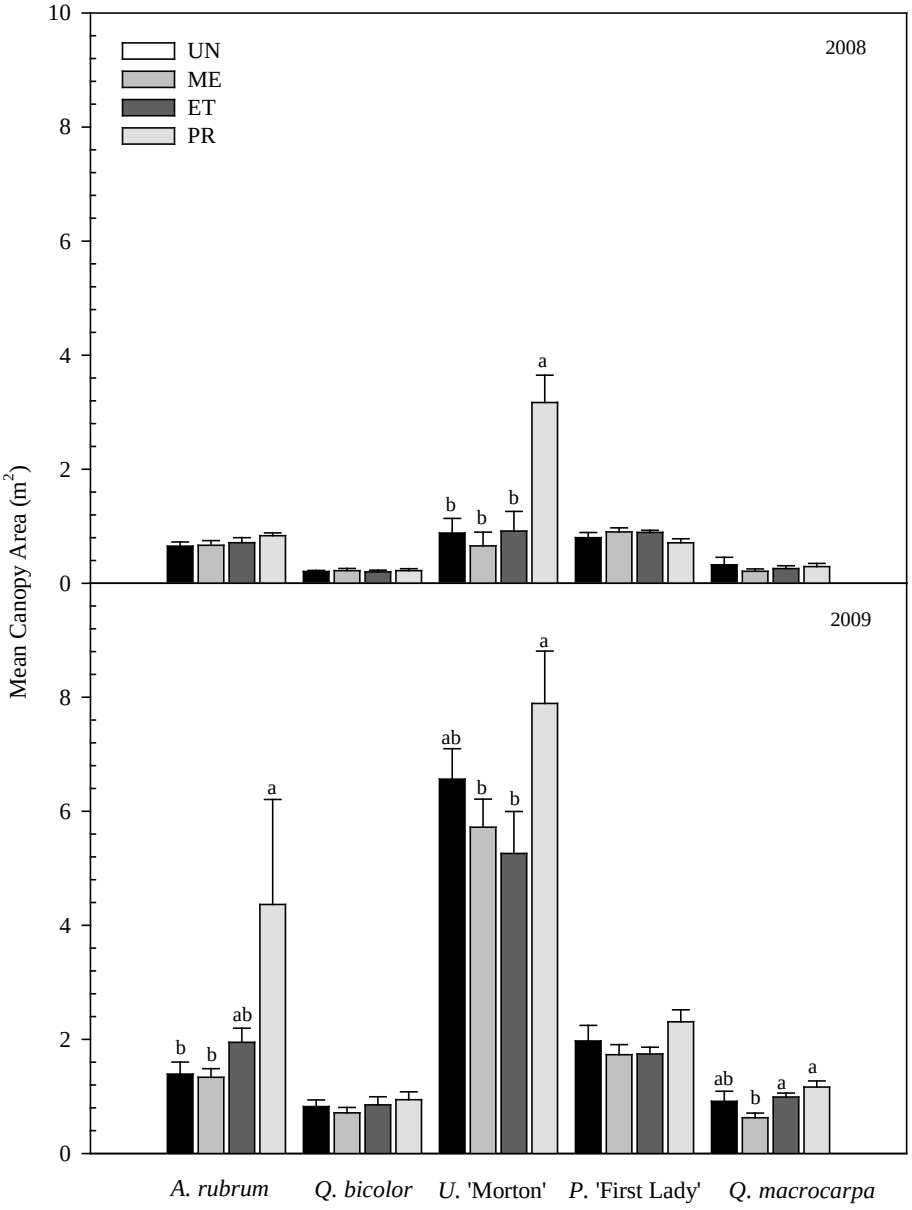

Figure 30. Mean canopy area (m^2) for *Acer rubrum* L., *Quercus bicolor* Willd., *Ulmus* 'Morton' (Accolade®) (*Ulmus japonica* (Rehd.) Sarg. x *Ulmus wilsoniana* Schneid.), *Prunus* 'First Lady' (*Prunus xincam* x *Prunus campanulata*) L. and *Quercus macrocarpa* Michx. trees growing in a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding) for the first (2008) and second (2009) growing seasons. (n=6) Means followed by the same letter within a species for each sampling event are not significantly different at the α=0.05 level (comparisonwise), using mean comparison by protected (P<0.1) LSD.

transplanting mean canopy area of *U.* 'Morton' trees was 383% greater in the highly rehabilitated PR treatment as compared to canopy of trees in the ME treatment. Unlike *U.* 'Morton,' however, both *Quercus* species are generally slow to establish (Udawatta 2005). They grew very little during the first growing season and no treatment effects were observed. Likewise, no treatment effects were observed for *A. rubrum* and *P.* 'First Lady' in the first growing season. After the second growing season, however, mean canopy area was greater in the PR treatment than in the ME treatment for *A. rubrum*, *U.* 'Morton' and *Q. macrocarpa*. Presumably, the lower soil bulk density in the PR treatment was associated with improved soil pore volume, aeration and infiltration and reduced mechanical impedance, thereby allowing for improved early root growth and development. For all species except for *U.* 'Morton', no significant canopy area differences were observed between PR and ET after the second growing season. Long-term monitoring of canopy area is needed to reveal treatment effects, especially in the slower growing species.

Cumulative cross-sectional trunk area (Figure 31) and trunk cross-sectional area increases (Table 7) are presented and discussed separately. Cross-sectional truck area (cm^2) was greater in the PR treatment in *A. rubrum* and *U.* 'Morton' in the first and second post-transplant season and in *Q. macrocarpa* in the second post-transplant season (Figure 31). The most marked cross-sectional area increase (Table 7) was observed in the PR treatment in 2009 for *U.* 'Morton'. Long-term measurements will be needed to see how the various treatments will influence size attainment at 15 or 20 years, the period during which canopy standards are typically set (McPherson 2001).

All treatment plot pH ranges fall within the purported pH tolerance of *A. rubrum* (pH=4.3-6.5) (Dirr 1998) with the exception of the 15.3–20.3 cm depth of the PR treatment (pH

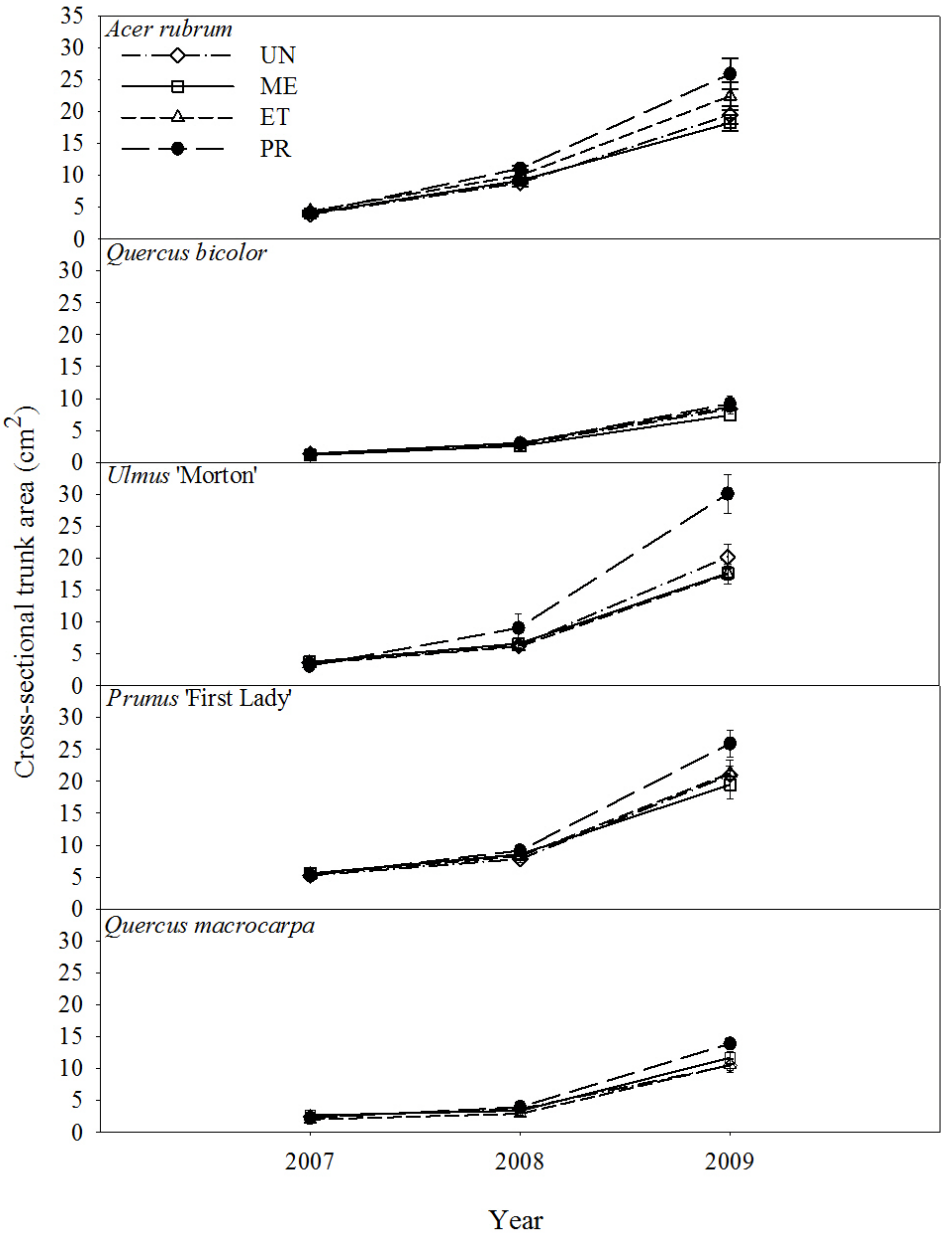

Figure 31. Cross-sectional trunk area at transplanting and after one (2008) and two (2009) years of growth for *Acer rubrum* L., *Quercus bicolor* Willd., *Ulmus* 'Morton' (Accolade®) (*Ulmus japonica* (Rehd.) Sarg. x *Ulmus wilsoniana* Schneid.), *Prunus* 'First Lady' (*Prunus xincam* x *Prunus campanulata*) L. and *Quercus macrocarpa* Michx. trees growing in a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding). (n=6) (See Table 3 for cross-sectional trunk area increases for the first and second year growing seasons.)

Table 7. Mean annual cross-sectional trunk area increase (cm^2) and standard error (in parentheses) for *Acer rubrum* L., *Quercus bicolor* Willd., *Ulmus* 'Morton' (Accolade®) (*Ulmus japonica* (Rehd.) Sarg. × *Ulmus wilsoniana* Schneid.), *Prunus* 'First Lady' (*Prunus xincam* × *Prunus campanulata*) L. and *Quercus macrocarpa* Michx. trees growing in a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding) for the first (2008) and second (2009) growing seasons. n=6. (See Figure 2 for cross-sectional trunk area plots.)

	Mean Annual Cross-Sectional Trunk Area Increase[z] (cm^2)	
	2008	2009
Acer rubrum		
UN	4.92 (0.44) b	10.67 (1.03) ab
ME	5.16 (0.50) b	9.01 (1.02) b
ET	5.63 (0.93) ab	12.42 (1.31) ab
PR	6.98 (0.29) a	14.83 (2.21) a
Quercus bicolor		
UN	1.48 (0.32)	5.52 (0.91)
ME	1.41 (0.13)	4.84 (0.17)
ET	1.67 (0.23)	5.64 (0.76)
PR	1.78 (0.22)	6.19 (1.05)
Ulmus 'Morton'		
UN	2.68 (0.53) b	13.88 (1.52) b
ME	2.90 (0.57) b	11.02 (0.72) b
ET	2.70 (0.41) b	11.35 (1.23) b
PR	5.92 (0.94) a	21.04 (2.17) a
Prunus 'First Lady'		
UN	2.56 (0.50)	13.18 (1.81) ab
ME	2.97 (0.49)	10.92 (1.64) b
ET	2.83 (0.33)	13.02 (1.01) ab
PR	3.88 (0.45)	16.78 (1.61) a
Quercus macrocarpa		
UN	1.21 (0.24) ab	6.8 (0.67) b
ME	0.73 (0.22) b	8.27 (0.76) ab
ET	0.87 (0.13) b	7.64 (0.72) b
PR	1.70 (0.33) a	9.93 (0.63) a

[z] Means followed by the same letter within a species are not significantly different at the α=0.05 level (comparisonwise), using mean comparison by protected (P<0.1) LSD.

= 7.06). All treatment soil pH ranges fall within the *Q. macrocarpa*, *U.* 'Morton,' *P.* 'First Lady', and *Q. bicolor* tolerances. Therefore, treatment pH differences did not likely inhibit or enhance tree growth in the first two growing seasons. Growth differences likely correspond instead to lowering bulk density and increases in organic matter, both of which contribute to increased macroporosity (Gomez et al. 2002; Greacen and Sands 1980).

Physiological Measurements

The soil treatments had no statistically significant effect on mean I-Ψ for first or second year for either *A. rubrum* or *Q. bicolor* (Table 8) with one exception. In the second growing season, the greatest I-Ψ was observed for *A. rubrum* in the PR and ET treatments while the least deficit was observed in the ME and UN treatments. The large mean canopy area measured in the PR treatment for *A. rubrum* may explain the greater deficit. While it was expected that integrated whole day water stress response in the UN and PR treatments would be lower than the ME, hormonal root signals in compacted soil have also been documented to decrease stomatal conductance and ultimately reduce transpirational loss and overall shoot water deficits (Kozlowski 1999). Both ABA and ethylene have been shown to increase in plants in response to soil compaction (Mulholland et al. 1996), suggesting root-to-shoot responses to mechanical impedance. Plots of mean Ψ_{leaf} daily patterns for *A. rubrum* and *Q. bicolor* (Figures 32 and 33, respectively) reveal generally similar daily patterns of water stress among treatments for both species, although UN *A. rubrum* trees appear to have somewhat less negative mid-day Ψ_{leaf} in July 2008 and UN and ME trees had less negative mid-day Ψ_{leaf}. Statistical analysis of mean leaf water potential at pre-dawn and mid-day (peak) time intervals (Table 9) did not reveal reduced water deficit in the PR treatments as was expected. Although we expected improved root penetration with PR, compacted soil may have held more water near the surface and actually led

Table 8. Mean integrated whole day water stress (I-Ψ) and photosynthesis (Ps) and standard error (in parentheses) for *Acer rubrum* L. and *Quercus bicolor* Willd. in a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding) in the first (2008) and second year (2009) growing season. (n=6)

Species	Soil Treatment	Integrated Whole Day Water Stress (I-Ψ) [Z, Y]		
		July 19, 2008	October 1, 2008	August 15, 2009
A. rubrum				
	UN	135.9 (3.87)	92.2 (4.08)	98.5 (3.42) b
	ME	144.5 (7.93)	91.6 (3.29)	98.9 (3.04) b
	ET	141.8 (4.54)	92.0 (3.30)	109.3 (1.71) a
	PR	137.7 (6.80)	84.8 (4.19)	115.8 (3.4) a
Q. bicolor				
	UN	89.1 (12.64)	131.9 (4.94)	158.5 (5.17)
	ME	111.2 (8.73)	131.4 (4.60)	169.9 (7.15)
	ET	103.4 (7.35)	131.5 (4.69)	161.5 (4.98)
	PR	108.7 (6.71)	123.1 (7.08)	170.4 (5.99)

Species	Soil Treatment	Ps (μmol $CO_2/m^2/s$) [Z]		
		May 27, 2008	September 13, 2008	September 2, 2009
A. rubrum				
	UN	4.78 (1.63)	11.86 (0.81)	10.31 (0.65)
	ME	5.78 (1.15)	12.66 (1.86)	10.64 (1.58)
	ET	4.77 (0.84)	12.88 (0.50)	11.02 (1.73)
	PR	5.80 (0.64)	13.14 (2.02)	10.41 (0.74)
Q. bicolor				
	UN	4.17 (0.72)	12.58 (0.80) c	16.279 (0.90)
	ME	4.15 (0.38)	15.77 (0.86) b	17.67 (1.25)
	ET	3.77 (0.45)	15.50 (0.81) b	15.72 (1.13)
	PR	3.82 (0.53)	19.51 (0.88) a	19.78 (0.87)

[Z] Means followed by the same letter within a species for each sampling date (shown above) are not significantly different at the α=0.05 level (comparisonwise), using mean comparison by protected (P<0.1) LSD

[Y] Note: Unitless measurement.

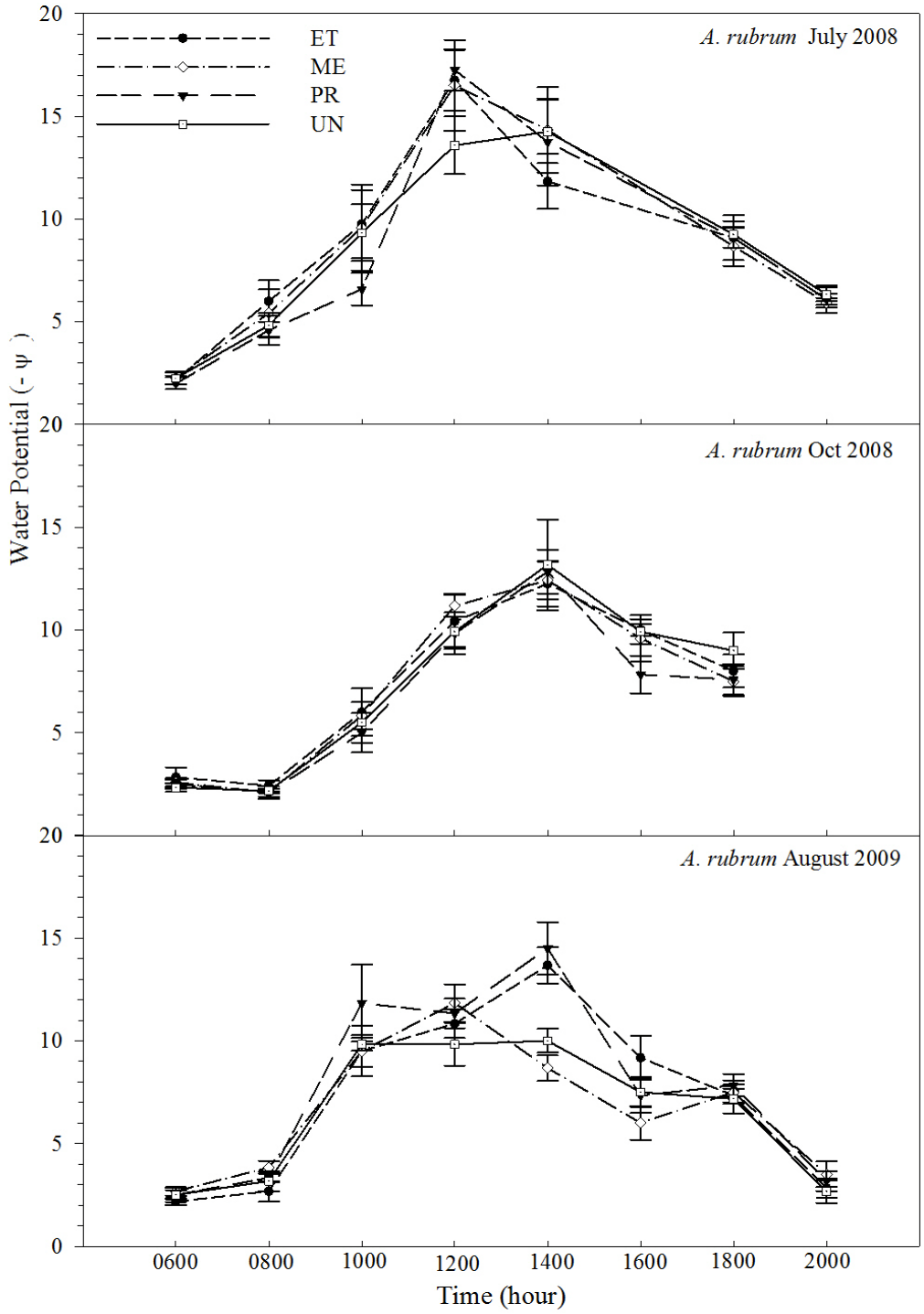

Figure 32. Mean *A. rubrum* leaf water potential ($-\psi_{LEAF}$) and standard errors (in parentheses) by two-hour time intervals from pre-dawn to dusk in a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding) for the first (2008) and second (2009) growing seasons. (n=6)

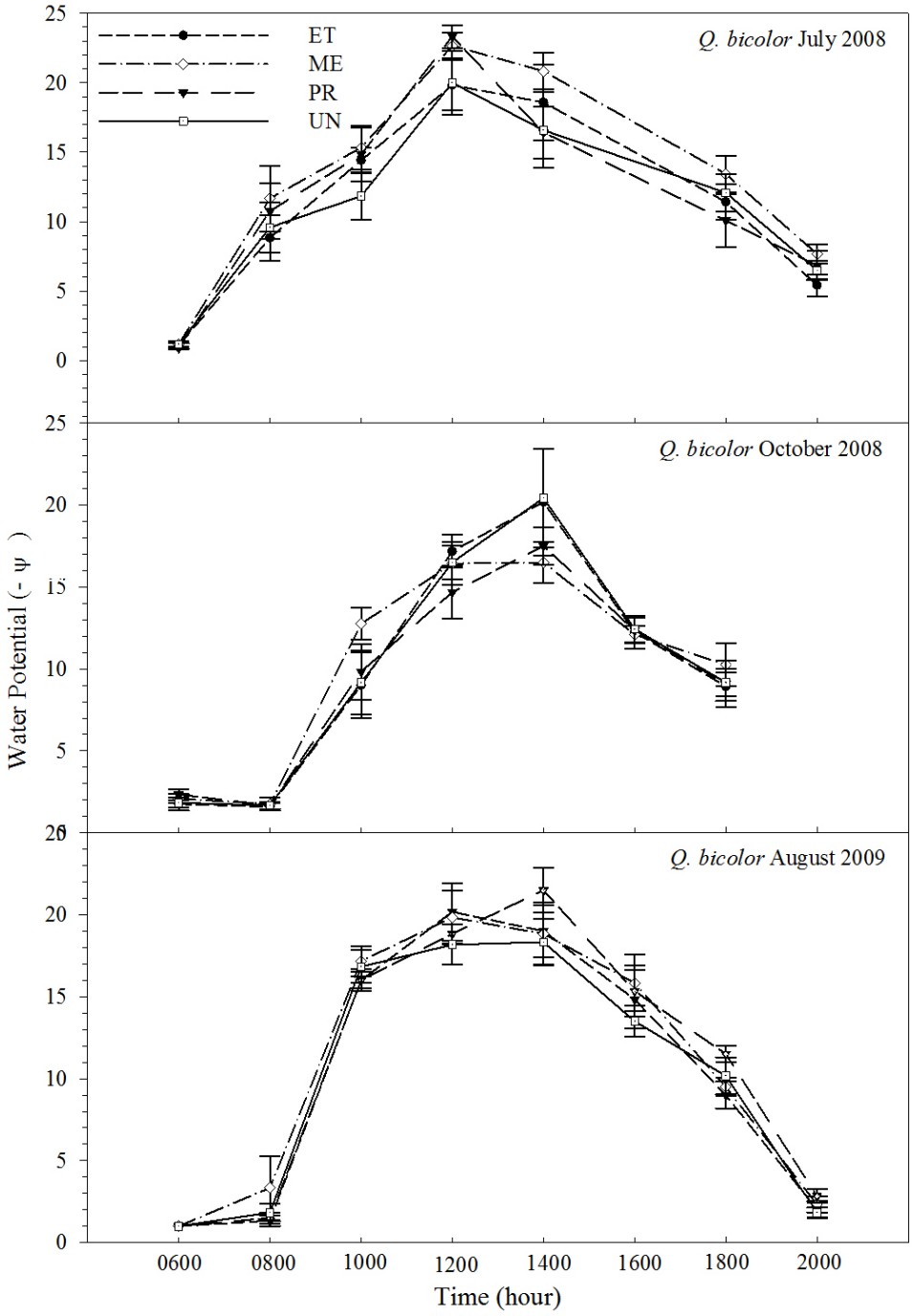

Figure 33. Mean *Q. bicolor* leaf water potential ($-\psi_{LEAF}$) and standard errors (in parentheses) by two-hour time intervals from pre-dawn to dusk in a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding) for the first (2008) and second (2009) growing seasons. (n=6)

Table 9. Mean pre-dawn and mid-day leaf water potential ($-\Psi_{leaf}$) and standard errors (in parentheses) for *Acer rubrum* L. and *Quercus bicolor* Willd. in a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding) in the first (2008) and second year (2009) growing season. (n=6) (See Figures 32 and 33 for daily water potential curves using the means of each time interval).

	Mean Leaf Water Potential ($-\Psi_{leaf}$)[z]		
	July 2008	October 2008	August 2009
Acer rubrum			
Pre-dawn	0600 hrs	0600 hrs	0600 hrs
UN	2.25 (0.28)	2.33 (0.21)	2.50 (0.34)
ME	2.25 (0.31)	2.58 (0.20)	2.67 (0.21)
ET	2.17 (0.21)	2.83 (0.48)	2.17 (0.17)
PR	2.00 (0.29)	2.50 (0.22)	2.50 (0.22)
Mid-day	1400 hrs	1400 hrs	1200 hrs
UN	14.25 (1.54)	13.17 (2.21)	9.83 (1.05)
ME	14.33 (2.08)	12.42 (0.91)	11.83 (0.91)
ET	11.83 (1.35)	12.25 (1.10)	10.83 (0.70)
PR	13.75 (2.11)	12.83 (1.07)	11.33 (0.71)
Quercus bicolor			
Pre-dawn	0600 hrs	0600 hrs	0600 hrs
UN	1.17 (0.21)	1.83 (0.31)	1.00 (0)
ME	1.17 (0.25)	2.08 (0.27)	1.00 (0)
ET	1.08 (0.15)	1.75 (0.40)	1.00 (0)
PR	0.92 (0.08)	2.33 (0.33)	1.00 (0)
Mid-day	1400 hrs	1400 hrs	1200 hrs
UN	16.58 (2.73)	20.42 (3.02)	18.17 (1.22)
ME	20.83 (1.30)	16.50 (1.26)	19.83 (1.62)
ET	18.58 (2.75)	20.17 (1.74)	20.17 (1.74)
PR	16.42 (1.85)	17.50 (1.13)	18.83 (0.60)

[z] Means followed by the same letter within a species for each sampling date (shown above) are not significantly different at the α=0.05 level (comparisonwise), using mean comparison by protected (P<0.1) LSD

to drought resistance at times during this early stage of establishment. However, we did not characterize soil water content.

Photosynthesis rates for all treatments of both *A. rubrum* and *Q. bicolor* in May 2008 were low and not significantly different (Table 8). These low rates were likely a result of transplant shock. Soil treatment effects on *A. rubrum* photosynthesis rates were not evident in September 2008 or 2009. In September 2008, *Q. bicolor* in the PR treatment had the highest photosynthesis rate of all treatment groups. No consistent treatment differences were observed in chlorophyll content index or fluorescence for either species in the first and second year growing seasons (Table 10).

4.4 Conclusions

Our results support the hypothesis that more intensive rehabilitative soil treatment can improve urban soil physical properties, urban tree growth, and canopy development during establishment and early growth. Of the three rehabilitation treatments compared in this study, only the PR treatment reduced bulk density of severely compacted subsoil at a depth of 15.2-20.3 cm, the soil layer soil just below the added topsoil. The mean bulk density of this subsoil layer was 1.34 g/cm^3 which is below reported root-limiting thresholds for loam soil (Greacen and Sands 1980). The preliminary indication is that the added level of effort required in the PR treatment does have a significant impact on improving soil physical properties.

Mean canopy area in the PR treatment was greater than the ME treatment for *A. rubrum, U.* 'Morton', and *Q. macrocarpa* after the second year growing season after transplant. No statistically significant differences were observed between canopy area in the ET and PR plots except for *U.* 'Morton' after the first two years of growth. Mean cross-sectional truck area

Table 10. Mean chlorophyll content and fluorescence and standard errors (in parentheses) for *Acer rubrum* L., *Quercus bicolor* Willd., *Ulmus* 'Morton' (Accolade®) (*Ulmus japonica* (Rehd.) Sarg. x *Ulmus wilsoniana* Schneid.), *Prunus* 'First Lady' (*Prunus xincam* x *Prunus campanulata*) L. and *Quercus macrocarpa* Michx. trees growing in a control (UN = undisturbed) and 3 soil remediation treatments for severely compacted soil (ME = minimum effort, ET = enhanced topsoil, and PR = profile rebuilding) for the first (2008) and second (2009) growing seasons. (n=6)

		Chlorophyll Content Index [X, Z]			Fluorescence (Fv/Fm) [Y, Z]	
Species	Soil Treatment	July 11, 2008	September 20, 2008	August 14, 2009	September 21, 2008	August 18, 2009
Acer rubrum	UN	40.91 (0.38)	43.20 (1.64)	45.80 (1.80)	0.75 (0.012)	0.78 (0.120)
	ME	41.43 (1.19)	42.84 (2.09)	40.02 (2.77)	0.73 (0.032)	0.78 (0.006)
	ET	42.80 (2.03)	44.13 (1.56)	45.27 (0.96)	0.71 (0.014)	0.77 (0.012)
	PR	43.53 (1.60)	47.38 (1.53)	44.73 (1.29)	0.77 (0.014)	0.79 (0.012)
Quercus bicolor	UN	42.20 (1.22)	43.98 (1.49)	43.98 (1.30)	0.75 (0.013)	0.8 (0.006)
	ME	40.93 (0.77)	42.33 (1.48)	43.00 (1.60)	0.74 (0.015)	0.77 (0.004)
	ET	41.12 (1.59)	43.87 (2.07)	44.28 (0.97)	0.74 (0.014)	0.78 (0.007)
	PR	42.12 (1.39)	42.52 (1.62)	45.08 (1.28)	0.73 (0.009)	0.78 (0.010)
Ulmus 'Morton'	UN	55.28 (0.80) a	57.13 (1.66)	59.35 (1.83)	0.78 (0.015) a	0.81 (0.003)
	ME	52.12 (1.43) ab	56.06 (1.06)	58.33 (0.89)	0.73 (0.009) b	0.81 (0.011)
	ET	52.46 (1.20) ab	56.78 (1.22)	59.23 (1.15)	0.73 (0.015) b	0.77 (0.026)
	PR	50.07 (1.75) b	59.45 (1.48)	58.88 (0.09)	0.73 (0.022) ab	0.81 (0.012)
Prunus 'First Lady'	UN	48.59 (1.42)	54.19 (2.01)	53.25 (1.30) a	0.78 (0.020)	0.81 (0.007)
	ME	49.02 (2.09)	51.92 (1.31)	49.32 (1.01) b	0.79 (0.012)	0.82 (0.008)
	ET	50.95 (2.12)	53.40 (1.78)	50.27 (0.52) b	0.81 (0.007)	0.82 (0.014)
	PR	44.98 (0.47)	54.48 (1.03)	51.38 (0.84) ab	0.79 (0.011)	0.81 (0.009)
Quercus macrocarpa	UN	42.99 (2.05)	47.94 (1.71)	53.03 (2.21)	0.75 (0.007) ab	0.81 (0.797)
	ME	38.83 (0.62)	43.41 (2.24)	48.47 (1.80)	0.77 (0.010) a	0.80 (0.005)
	ET	41.23 (1.72)	45.43 (1.64)	47.77 (1.56)	0.73 (0.012) b	0.80 (0.009)
	PR	42.08 (2.00)	45.59 (2.44)	51.33 (1.75)	0.78 (0.009) a	0.81 (0.008)

[Z] Means followed by the same letter within a species for each sampling event are not significantly different at the α=0.05 level (comparisonwise), using mean comparison by protected (P<0.1) LSD.
[Y] Subsamples: 1 per tree
[X] Subsamples: 2 per tree (July and September 2008) and 3 per tree (August 2009)

increase was also greatest in the PR treatment for *A. rubrum*, *U.* 'Morton' and *Q. macrocarpa* after the second year growing season after transplant. Species variation in growth rate and environmental tolerance appeared to influence early growth treatment effects.

We believe these results are associated with the most reduced mechanical impedance of the PR soil, which would facilitate both greater root penetration and nutrient and water acquisition. However, future studies which include soil moisture measurements and measurements of soil physical properties over time are needed to determine the effects of these rehabilitation treatments on the plant soil-water relationships. Additionally, our C/N measurements indicate that the PR treatment facilitates greater integration of organic matter amendments into the soil profile than natural processes can achieve (Rolf 1994a). Greater tree height increase, cross-sectional trunk area, and canopy area observed for most species after the second growing season in the PR treatment are also likely attributed in part to improved aeration, nutrient and water availability, and permeability resulting from organic matter amendment.

The general lack of differences in physiological parameters in the first and second year growing season, despite the presence of roots in various treatments at varying depths, suggests the soil conditions in the planting holes were adequate to meet the basic nutrient and water needs of the trees. Weather patterns were generally favorable at the site in the growing seasons of 2008 and 2009. Treatment effects on physiological parameters would likely be more evident in periods of prolonged drought or rain. Long-term data that include time periods of severe weather (drought or rain) are ultimately needed to best evaluate the effects of soil conditions on long-lived species such as shade trees.

Chapter Five: Conclusions and Recommendations

In this study, the effects of typical and improved methods of soil restoration on tree growth and soil properties were evaluated for two years after transplanting. We found that more intensive rehabilitative soil treatment improved urban soil physical properties, urban tree growth and canopy development during this period of establishment and early growth. Of the three rehabilitation treatments compared in this study, only the PR treatment reduced bulk density of severely compacted subsoil at a depth of 15.2-20.3 cm, the soil layer soil just below the added topsoil. The mean bulk density of this subsoil layer was 1.34 g/cm^3 which is below reported root-limiting thresholds for a loamy soil. However, future studies which include soil moisture measurements and measurements of soil physical properties over time are needed to determine the effects of these rehabilitation treatments on plant soil-water relationships.

Mean canopy area was greater in the PR treatment than in the ME treatment for *A. rubrum, U.* 'Morton', and *Q. macrocarpa* after the second year growing season after transplant. Mean cross-sectional trunk area increase was greatest in the PR treatment for treatment for *A. rubrum, U.* 'Morton' and *Q. macrocarpa* after the second year growing season after transplant. Species variation in growth rate and environmental tolerance appeared to influence early growth treatment effects.

Increases in growth in the first two years after transplant are believed to be associated with improved macroporosity and reduced mechanical impedance of the soil, which would facilitate both greater root penetration and nutrient and water acquisition. C/N measurements and

CEC and nutrient data also indicate that the PR treatment facilitates greater integration of organic matter amendments into the soil profile than natural processes can achieve (Rolf 1994a). Greater tree height increase, cross-sectional trunk area, and canopy area observed for most species after the second growing season in the PR treatment are also likely attributed in part to improved aeration, nutrient and water availability, and permeability resulting from organic matter amendment.

Treatment effect on rooting depth after two years varied by species. Greater root presence was observed in deeper soil layers of ET and PR treatments for *A. rubrum* and of UN and PR for *Q. bicolor;* root distribution was not measured for other species. Roots were observed but not expected in the compacted subsoil layer of ME and ET treatment; it is possible the planting holes served as a conduit for the roots to penetrate this layer. Additionally, minirhizotron measurements only capture a small proportion of the root system, and measurement variability is high. Nonetheless, there was evidence that soil compaction restricted root penetration in both species, and that, for *Q. bicolor*, root exploration of deeper soil layers was restricted in soil subjected to typical soil preparation practices, represented by the ME and ET treatments.

The general lack of differences in physiological parameters in the first and second year growing season, despite the effects of the compacted soil, suggests that basic tree nutrient and water needs were met in all treatments. Long-term data that include time periods of severe weather (drought or rain) are ultimately needed to best evaluate the effects of soil conditions on long-lived species such as shade trees.

First and second year data suggest that soil improvement methods can be used to improve tree establishment and growth; however, long-term data is needed at this research site to assess long-term treatment effects and correlate growth data to levels of rehabilitative effort in order to assist urban foresters to make decisions regarding what levels of rehabilitative effort can ensure the desired tree canopies and benefits. Long-term monitoring of soil physical and chemical properties will also help evaluate how the PR treatment can facilitate natural, time-dependent soil forming processes and affect soil bulk density and organic matter content

Literature Cited

Cooperative Forestry Assistance Act. 1978. 16 U.S.C. 2101 (note). USA

America the Beautiful Act. 1990. Subtitle C (§§ 1261–1266) of title XII of Pub. L. 101–624.

Alberty CA, Pellett HM, Taylor DH (1984) Characterization of soil compaction at construction sites and woody plant response. Journal of environmental horticulture 2: 48-53

Albiach R (2001) Organic matter components and aggregate stability after the application of different amendments to a horticultural soil. Bioresource technology 76: 125

Baker NR (2008) Chlorophyll fluorescence: a probe of photosynthesis in vivo. Annual Review of Plant Biology 59: 89-113

Bartens J (2008) Can Urban Tree Roots Improve Infiltration through Compacted Subsoils for Stormwater Management? Journal of environmental quality 37: 2048

Bassett IE, Simcock RC, Mitchell ND (2005) Consequences of soil compaction for seedling establishment: implications for natural regeneration and restoration. Austral Ecology 30: 827-833

Beatty RA, Heckman CT (1981) Survey of urban tree programs in the United States. Urban Ecology 5: 81-102

Bernatzky A (1974) Trees on building sites. Landscape and Planning 1: 255-288

Bragg PL (1983) A comparison of methods, including angled and vertical minirhizotrons, for studying root growth and distribution in a spring oat crop. Plant and soil 73: 435-440

Bramley H (2003) Floodwater infiltration through root channels on a sodic clay floodplain and the influence on a local tree species *Eucalyptus largiflorens*. Plant and soil 253: 275-286

Braun S (1998) Soil amendments for plantings of urban trees. Soil & tillage research 49: 201

Corley WL (1984) Soil Amendments at Planting. Journal of environmental horticulture 2: 27-30

Craul PJ (1985) A description of urban soils and their desired characteristics. Journal of Arboriculture 11: 330-339

Craul PJ (1992) Urban Soil in Landscape Design. John Wiley & Sons, Inc., New York

Craul PJ (1994) Soil compaction on heavily used sites. Journal of Arboriculture 20: 69-74

Daddow RL, Warrington GE (1983) Growth Limiting Soil Bulk Densities as Influenced by Soil Texture. USDA-Forest Service Watershed Systems Development Group, Fort Collins, Colorado

Day SD, Bassuk NL (1994) A review of the effects of soil compaction and amelioration treatments on landscape trees. Journal of Arboriculture 20: 9-17

Day SD, Bassuk NL, Van Es H (1995) Effects of four compaction remediation methods for landscape trees on soil aeration, mechanical impedance and tree establishment. Journal of environmental horticulture 13: 64-71

Day SD, Seiler JR, Persaud N (2000) A comparison of root growth dynamics of silver maple and flowering dogwood in compacted soil at differing soil water contents. Tree Physiology 20: 257-263

Day SD, Wiseman PE, Dickinson SB, Harris JR (2010a) Contemporary Concepts of Root System Architecture of Urban Trees. Arboriculture & Urban Forestry 36: 149-159

Day SD, Wiseman PE, Dickinson SB, Harris JR (2010b) Tree Root Ecology in the Urban Environment and Implications for a Sustainable Rhizosphere. Arboriculture & Urban Forestry 36: 193-205

De Kimpe CR, Morel J-L (2000) Urban soil management: A growing concern. Soil Science 165: 31-40

Diaz E (1994) Formation of stable aggregates in degraded soil by amendment with urban refuse and peat. Geoderma 63: 277

Dirr M (1998) Manual of woody landscape plants : their identification, ornamental characteristics, culture, propagation and uses. Stipes Pub., Champaign, Ill.

Fite KL (2008) Impacts of Root Invigoration™ and Its Individual Components on the Performance of Red Maple (Acer rubrum). Plant and Environmental Sciences. Clemso University, Clemson, SC, p 137

Foster RS, Blaine J (1978) Urban tree survival: trees in the sidewalk. Journal of Arboriculture 4: 14-17

Galbraith JM, Donovan PF (2005) Interactive GIS and Soil Survey of the Virginia Tech Kentland Farm in Montgomery County, Virginia. . pp Fieldwork by W. Edmonds and D. Gall, United States Department of Agriculture, Natural Resources Conservation Service, in cooperation with Virginia Polytechnic Institute and State University

Geiger JR (2004) The Large Tree Argument: The Case for Large Trees vs. Small Trees. Western Arborist 30: 14-15

Gomez A, Powers RF, Singer MJ, Horwath WR (2002) Soil Compaction Effects on Growth of Young Ponderosa Pine Following Litter Removal in California's Sierra Nevada. Soil Sci. Soc. Am. J. 66: 1334-1343

Greacen EL, Sands R (1980) Compaction of forest soils. A review. Australian Journal of Soil Research 18: 163-189

Haas RH, Dodd JD (1972) Water-Stress Patterns in Honey Mesquite. Ecology 53: 674-680

Hascher W (2007) Effects of Soil Decompaction and Amendment on Root Growth and Architecture in Red Maple (Acer rubrum). Arboriculture & Urban Forestry 33: 428-432

Hillel D (1982) Introduction to Soil Physics. Academic Press, Inc. , New York

Horn R, Domzzal H, Slowinska-Jurkiewicz A, van Ouwerkerk C (1995) Soil compaction processes and their effects on the structure of arable soils and the environment. Soil and Tillage Research 35: 23-36

Huinink JTM (1998) Soil quality requirements for use in urban environments. Soil & Tillage Research

Hummel RL (1985) Amended backfills: Their cost and effect on transplant growth and survival. Journal of environmental horticulture 3: 76-79

Jim CY (1998) Urban soil characteristics and limitations for landscape planting in Hong Kong. Landscape and Urban Planning 40: 235-249

Johnson MG, Tingey DT, Phillips DL, Storm MJ (2001) Advancing fine root research with minirhizotrons. Environmental and Experimental Botany 45: 263-289

Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE (1997) Soil quality: a concept, definition, and framework for evaluation. . Soil Science Society of America journal. 61: p. 4-10

Kögel-Knabner I (2002) The macromolecular organic composition of plant and microbial residues as inputs to soil organic matter. Soil Biology and Biochemistry 34: 139-162

Kozlowski TT (1999) Soil compaction and growth of woody plants. Scandinavian Journal of Forest Research 14: 596-619

Macie EA, Hermansen LA (2002) Human Influences on Forest Ecosystems: The Southern Wildland-Urban Interface Assessment. In: Service UF (ed)

Matthews SN (2010) Movement behaviour of a forest songbird in an urbanized landscape: the relative importance of patch-level effects and body condition during migratory stopover. Landscape ecology 25: 955-965

McPherson EG (2001) Sacramento's parking lot shading ordinance: environmental and economic costs of compliance. Landscape and Urban Planning 57: 105-123

Moffat AJ (1997) The effectiveness of cultivation using the winged time on restored sand and gravel workings. Soil & tillage research 40: 111

Mulholland BJ, Black CR, Taylor IB, Roberts JA, Lenton JR (1996) Effect of soil compaction on barley (Hordeum vulgare L.) growth. Journal of Experimental Botany 47: 539-549

Nowak DJ, McBride JR, Beatty RA (1990) Newly planted street tree growth and mortality. Journal of Arboriculture 16: 124

Nowak DJ, Noble MH, Sisinni. SM, Dwyer JF (2001) People and Trees: Assessing the US Urban Forest Resource. Journal of Forestry 99: 37-42

Pagliai M (2004) Soil structure and the effect of management practices. Soil & tillage research 79: 131

Patterson JC (1977) Soil compaction--effects on urban vegetation. Journal of Arboriculture 3: 161-167

Paul W. Adams, Froehlich HA (1981) Compaction of Forest Soils. Pacific Northwest Extension Publication 217, Corvallis: Oregon State University

Pavao-Zuckerman MA (2008) The Nature of Urban Soils and Their Role in Ecological Restoration in Cities. Restoration Ecology 16: 642-649

Piccolo A, Mbagwu JSC (1999) Role of hydrophobic components of soil organic matter in soil aggregate stability. Soil Science Society of America Journal 63: 1801-1810

Pittenger DR, Stamen T (1980) Effectiveness of methods used to reduce harmful effects of compacted soil around landscape trees. Journal of Arboriculture 16: 55-57

Pouyat RV, Yesilonis, I.D., Russell-Anelli, J., Neerchal, N.K. (2007) Soil Chemical and Physical Properties That Differentiate Urban Land-Use and Cover Types. Soil Science Society of America Journal 71: 1010-1019

Powers RF, Andrew Scott D, Sanchez FG, Voldseth RA, Page-Dumroese D, Elioff JD, Stone DM (2005) The North American long-term soil productivity experiment: Findings from the first decade of research. Forest Ecology and Management 220: 31-50

Powers RF, D.H.Alban, Miller RE, Tiarks AE, Wells CG, Avers PE, Cline RG, R.O.Fitzgerald, N.S. Loftus J (1990) Sustaining site productivity in North American forests: Problems and prospects. 7th North American Forest Soils Conference. University of British Columbia, Vancouver, B.C., pp 49-79

Randrup TB (1997) Soil compaction on construction sites. Journal of Arboriculture 23: 208

Randrup TB, Dralle K (1997) Influence of planning and design on soil compaction in construction sites. Landscape and Urban Planning 38: 87-92

Rivenshield A, Bassuk NL (2007) Using Organic Amendments to Decrease Bulk Density and Increase Macroporosity in Compacted Soils. Arboriculture & Urban Forestry 33: 140-146

Rolf K (1992) Soil physical effects of pneumatic subsoil loosening using a Terralift soil aerator. Journal of Arboriculture 18: 235

Rolf K (1994a) A review of preventative and loosening measures to alleviate soil compaction in tree planting areas. Arboricultural Journal 18: 431-448

Rolf K (1994b) Soil compaction and loosening effects on soil physics and tree growth. In: Watson GW, Neely D (eds) The Landscape Below Ground. International Society of Arboriculture, Champaign, IL, pp 131-148

Sæbø A, Ferrini F (2006) The use of compost in urban green areas - A review for practical application. Urban Forestry & Urban Greening 4: 159-169

Schabenberger O, Pierce FJ (2002) Contemporary Statistical Models for the Plant and Soil Sciences. CRC Press LLC, Boca Raton, FL

Scharenbroch BC, Lloyd JE, Johnson-Maynard JL (2005) Distinguishing urban soils with physical, chemical, and biological properties. Pedobiologia 49: 283-296

Schindelbeck RR, van Es HM, Abawi GS, Wolfe DW, Whitlow TL, Gugino BK, Idowu OJ, Moebius-Clune BN (2008) Comprehensive assessment of soil quality for landscape and urban management. Landscape and Urban Planning 88: 73-80

Short JR, Fanning DS, McIntosh MS, Foss JE, Patterson JC (1986) Soils of the Mall in Washington, DC: I. Statistical summary of properties. Soil Science Society of America Journal 50: 699-705

Sinnett D (2008) A comparison of cultivation techniques for successful tree establishment on compacted soil. Forestry (London) 81: 663-679

Sinnett D, Poole J, Hutchings TR (2006) The efficacy of three techniques to alleviate soil compaction at a restored sand and gravel quarry. Soil use and management 22: 362-371

Smalley TJ (1995) Effect of backfill amendment on growth of red maple. Journal of Arboriculture 21: 247-250

Smiley ET (2001) Terravent™: Soil fracture patterns and impact on bulk density. Journal of Arboriculture 27: 326-330

Smiley ET, Watson Gw, Fraedrich BR, Booth DC (1990) Evaluation of Soil Aeration Equipment. Journal of Arboriculture 16: 118-123

Smith KD, May PB, Moore GM (2001) The influence of compaction and soil strength on the establishment of four Australian landscape trees. Journal of Arboriculture 27: 1-7

Spoor G (2006) Alleviation of soil compaction: requirements, equipment and techniques. Soil use and management 22: 113-122

Taylor HM, Brar GS (1991) Effect of soil compaction on root development. Soil and Tillage Research 19: 111-119

Taylor HM, Roberson GM, Parker JJJ (1966) Soil Strength-Root Penetration Relations for Medium- To Coarse-Textured Soil Materials. Soil Science 102: 18-22

Tingey DT, Phillips DL, Johnson MG, Rygiewicz PT, Beedlow PA, Hogsett WE (2005) Estimates of Douglas-fir fine root production and mortality from minirhizotrons. Forest ecology and management 204: 359-370

Udawatta RP (2005) Growth of three oak species during establishment of an agroforestry practice for watershed protection. Canadian journal of forest research 35: 602-609

van Noordwijk M, Brouwer G, Harmanny K (1993) Concepts and methods for studying interactions of roots and soil structure. Geoderma 56: 351-375

Vepraskas MJ (1988) Bulk Density Values Diagnostic of Restricted Root Growth in Coarse-textured Soils. Soil Sci. Soc. Am. J. 52: 1117-1121

Vrscaj B, Poggio L, Marsan FA (2008) A method for soil environmental quality evaluation for management and planning in urban areas. Landscape and Urban Planning 88: 81-94

Walters R, Yawney H (1990) Acer rubrum L. . In: Burns R, Honkala B (eds) Silvics of North America: Volume 2, Hardwoods. Forest Service, United States Department of Agriculture Washington, DC, pp 60-69

Whitlow TH, Bassuk NL, Reichert DL (1992) A 3-Year Study of Water Relations of Urban Street Trees. Journal of Applied Ecology 29: 436-450

Xiao Q, McPherson EG (2002) Rainfall interception by Santa Monica's municipal urban forest. Urban Ecosystems 6: 291-302

Xiao Q, McPherson EG, Ustin SL, Grismer ME, Simpson JR (2000) Winter rainfall interception by two mature open-grown trees in Davis, California. Hydrological Processes 14: 763-784

Zhang B, Horn R, Hallett PD (2005) Mechanical Resilience of Degraded Soil Amended with Organic Matter. Soil Science Society of America Journal 69: 864-871

Zhu P (2008) Demand for urban forests in United States cities. Landscape and Urban Planning 84: 293

Zill DG (1985) Calculus with Analytic Geometry. Prindle, Weber & Schmidt, Boston

Zisa RP, Halverson HG, Stout BB (1980) Establishment and early growth of conifers on compact soils in urban areas

Appendix A: Shottower Loam and Slabtown Loam Soil Series

LOCATION SHOTTOWER VA

Established Series

Rev. DAG-WJE-DDR

09/2008

SHOTTOWER SERIES

The Shottower series consists of very deep, well drained, moderately permeable soils on high stream terraces. They formed in old alluvium derived from sandstone, quartzite, limestone, shale, and siltstone. Slopes range from 2 to 35 percent. Mean annual air temperature is 55 degrees F. Mean annual precipitation is 42 inches.

TAXONOMIC CLASS: Fine, kaolinitic, mesic Typic Paleudults

TYPICAL PEDON: Shottower loam - on a 3 percent convex west-facing slope in a cultivated field. (Colors are for moist soil.)

Ap--0 to 10 inches; brown (7.5YR 4/4) loam; moderate medium granular structure; friable, slightly sticky, slightly plastic; 10 percent rounded rock fragments; slightly acid; abrupt smooth boundary. (6 to 15 inches thick)

Bt1--10 to 19 inches; yellowish red (5YR 5/8) clay loam; moderate fine subangular blocky structure; friable, sticky, plastic; 3 percent rounded rock fragments; common faint clay films on faces of peds; strongly acid; clear smooth boundary.

Bt2--19 to 40 inches; red (2.5YR 4/6) clay; many coarse distinct yellowish red (5YR 5/6) mottles; strong fine subangular blocky structure; friable, sticky, plastic; 5 percent rounded rock fragments; many distinct clay films on faces of peds; strongly acid; diffuse smooth boundary.

Bt3--40 to 72 inches; red (2.5YR 4/6) clay; common coarse distinct yellowish brown (10YR 5/6) mottles; strong fine subangular blocky structure; firm, sticky, plastic; 10 percent rounded rock fragments; many distinct clay films on faces of peds; strongly acid. (Combined thickness of the Bt horizon is 60 to 90 inches.)

TYPE LOCATION: Wythe County, Virginia; about 0.83 mile southeast of the junction of VA-630 and VA-631 and 1.25 miles southwest of the junction of US-52 and VA-619.

RANGE IN CHARACTERISTICS: Solum thickness and depth to bedrock are more than 60 inches. Rounded rock fragments of sandstone and quartzite range from 0 to 35 percent in the A and Bt horizons, and from 0 to 60 percent below 40 inches. Reaction ranges from extremely acid through moderately acid.

The A horizon, where present, is less than 3 inches thick and has hue of 5YR through 10YR, value of 2 or 3, and chroma of 2 or 3. It is silt loam, loam, or fine sandy loam in the fine-earth fraction.

The Ap horizon has hue of 2.5YR through 10YR, value of 3 through 5, and chroma of 3 or 4. It is silt loam, loam, or fine sandy loam in the fine-earth fraction, with silty clay loam, clay loam, or sandy clay loam in severely eroded areas.

The Bt horizon has hue of 10R through 7.5YR, value of 4 or 5, and chroma of 4 through 8. It is clay, silty clay, silty clay loam, clay loam or sandy clay loam in the fine-earth fraction.

COMPETING SERIES: Christiana, Dunmore, and Tumbling series are in the same family. Christiana soils formed in unconsolidated sediments on the upper coastal plain and do not have rock fragments. Dunmore soils formed in residuum from limestones and dolomites and rock fragments are dominantly chert. Tumbling soils formed in colluvium and have semirounded rock fragments.

GEOGRAPHIC SETTING: Shottower soils are on high stream terraces. Slopes range from 2 to 35 percent. The soils formed in old alluvium derived primarily from materials weathered from limestones, shales, siltstones, sandstones, and quartzites mixed with materials derived from crystalline rocks. Mean annual air temperature is 55 degrees F. Mean annual precipitation is 42 inches.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Allegheny, Austinville, Frederick, Groseclose, Litz, Marbie, and Wyrick series. Allegheny soils have less clay in the subsoil and are on low stream terraces. Austinville soils have darker subsoils and are on convex uplands. Chiswell and Litz soils are more shallow to bedrock and are on convex uplands. Frederick soils are on convex uplands with no rounded gravel or cobbles. Groseclose soils have thinner sola and occur on convex uplands. Marbie soils have Bx horizons and are in upland drainageways and depressions. Wyrick soils have less clay in the subsoil and are in upland drainageways and depressions.

DRAINAGE AND PERMEABILITY: Well drained. Runoff is slow to rapid. Permeability is moderate.

USE AND VEGETATION: These soils are used mainly for cropland. Major crops are corn, small grain, hay, and pasture.

DISTRIBUTION AND EXTENT: Limestone valleys in Virginia and possibly West Virginia, Maryland, and Tennessee. The series is of moderate extent.

MLRA OFFICE RESPONSIBLE: Morgantown, West Virginia

SERIES ESTABLISHED: Wythe County, Virginia, 1989.

REMARKS: Soils now within the range of the Shottower series were previously correlated as Braddock, Hiwassee, Masada, and Unison series in published soil surveys.

Lab data for the typical pedon has 52 percent kaolinite in the mineralogy control section.

Diagnostic horizons and features recognized in this pedon are: 1. Ochric epipedon - the zone from 0 to 10 inches (Ap horizon). 2. Argillic horizon - the zone from 10 to 72 inches (Bt horizon).

SIR = VA0275, VA0278 (COBBLY) MLRA = 128 REVISED 4/26/89; 9/08-increased slope range from 30% to 35%

National Cooperative Soil Survey
U.S.A.

http://www2.ftw.nrcs.usda.gov/osd/dat/S/SHOTTOWER.html

LOCATION SLABTOWN VA
Established Series
Rev. DDR, DGF
04/2004

SLABTOWN SERIES

The Slabtown series consists of deep, moderately well drained soils formed in the weathered material of mixed colluvium and underlying limestone residuum. Permeability is moderately slow. Slope ranges from 2 to 15 percent. Mean annual precipitation is about 37 inches, and mean annual air temperature is about 54 degrees F.

TAXONOMIC CLASS: Fine-loamy, mixed, semiactive, mesic Aquic Paleudalfs

TYPICAL PEDON: Slabtown on a southwest facing, 10 percent concave toeslope under pasture at a 1,900 foot elevation. (Colors are for moist soil unless otherwise stated)

Ap--0 to 9 inches; brown (10YR 4/3) silt loam; weak fine granular structure; friable, slightly sticky and non-plastic; common fine and very fine roots; common very fine pores; 10 percent semi-rounded chert and sandstone fragments; neutral; clear wavy boundary. (0 to 10 inches thick)

E--9 to 18 inches; yellowish brown (10YR 5/4) silt loam; weak fine and very fine subangular blocky structure; friable, slightly sticky and nonplastic; few fine and very fine roots; common very fine pores; few fine faint pale brown (10YR 6/3) iron depletions; 5 percent semi-rounded chert and sandstone fragments; 3 percent reddish brown (2.5YR 5/4) weathered rock fragments, moderately alkaline; clear smooth boundary. (0 to 12 inches thick)

BE--18 to 26 inches; yellowish brown (10YR 5/4) silt loam; moderate fine and very fine subangular blocky structure; friable, slightly sticky and slightly plastic; few very fine roots; many very fine pores; very patchy pale brown (10YR 6/3) and dark yellowish brown (10YR 4/4) ped coatings; 12 percent semi-rounded chert and sandstone fragments; 15 percent reddish brown (2.5YR 5/4) weathered rock fragments; few manganese stains on peds; moderately alkaline; clear smooth boundary. (5 to 15 inches thick)

Bt1--26 to 34 inches; yellowish brown (10YR 5/6) silt loam; moderate coarse prismatic structure parting to moderate, very thick platy; friable, some brittle areas, slightly sticky and slightly plastic; few very fine roots on prism faces; many very fine pores; few distinct brown (7.5YR 4/4) clay films; many fine distinct light gray (10YR 7/2) iron depletions; 2 percent semi-rounded chert and sandstone fragments; 5 percent reddish brown (2.5YR 5/4) weathered rock fragments; common manganese stains on peds; moderately alkaline; gradual smooth boundary.

Bt2--34 to 44 inches; strong brown (7.5YR 5/6) and light yellowish brown (10YR 6/4) gravelly silty clay loam; moderate coarse prismatic structure parting to moderate very thick platy; friable, some brittle areas, slightly sticky and slighty plastic; few very fine roots on prism faces; common very fine pores; few distinct brown (7.5YR 4/4) clay films; many fine distinct light gray (10YR 7/2) iron depletions; 18 percent rounded chert and sandstone fragments; 5 percent reddish brown (2.5YR 5/4) weathered rock fragments; many manganese stains on peds; moderately alkaline; clear smooth boundary. (Combined thickness of the Bt horizon is 15 to 45 inches)

2Bt3--44 to 75 inches; yellowish brown (10YR 5/8) clay; moderate very fine subangular blocky structure; friable, slightly sticky and plastic; common very fine pores; common prominent strong brown (7.5YR 5/6) clay films; common medium distinct yellowish red (5YR 5/8) iron concentrations; moderately alkaline.

TYPE LOCATION: Pulaski County, Virginia; approximately 3 miles north of the town of Pulaski, and 150 yards northwest of intersection of VA-645 and US-11.

RANGE IN CHARACTERISTICS: Depth to the discontinuity dominantly ranges from 30 to 50 inches. The solum thickness and depth to bedrock is more than 60 inches. Chert and sandstone rock fragments make up 2 to 35 percent of the volume above the lithologic discontinuity and 0 to 5 percent of the volume below the discontinuity. Reaction of the solum ranges from moderately acid to mildly alkaline in the A and upper B horizons and neutral to mildly alkaline in the lower horizons.

The A horizon has hue of 1OYR, value of 4 or 5 and chroma of 3 to 8. It is silt loam or loam.

The E horizon has hue of 10YR or 7.5Y, value of 4 or 5 and chroma of 3 to 8. It is loam or silt loam.

The B horizon above the discontinuity has hue of 1OYR or 7.5YR, value of 5 or 6 and chroma of 4 to 8. It is loam, silt loam, clay loam or silty clay loam.

The 2B horizon has hue of 1OYR to 5YR, value of 5 or 6, and chroma of 4 to 8. The lower part of some 2B horizons are multicolored. They are silty clay loam, silty clay or clay.

COMPETING SERIES: There are no other series in this family. Reedsburg soils are in a closely related family that is fine silty and superactive.

GEOGRAPHIC SETTING: Slabtown soils formed dominantly in colluvium from shale, sandstone, limestone and the underlying limestone residuum and are commonly on concave toeslopes and backslopes and at the heads of drains. Slope gradients range from 2 to 15 percent. The climate is humid continental. Mean annual air temperature ranges from 50 to 58 degrees F., mean annual precipitation ranges from 35 to 40 inches, and frost free days range from 145 to 180 days.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Carbo, Faywood, Frederick, Lodi, Lowell, Newbern, Poplimento, and Wurno soils. The Carbo, Faywood, Frederick, Lodi, Lowell, and Poplimento soils have a clayey particle-size control section. The Newbern soil has bedrock within a depth of 20 inches and the Wurno soil has bedrock within a depth of 40 inches.

DRAINAGE AND PERMEABILITY: Moderately well drained. The potential for surface runoff potential is medium to high. Permeability is moderately slow.

USE AND VEGETATION: These soils are mostly cleared and used for hay and pasture. A very small portion is wooded or cultivated.

DISTRIBUTION AND EXTENT: MLRA 128, 147. In the Appalachian Ridges and Valleys areas of Virginia and possible Kentucky, Pennsylvania, Tennessee, and West Virginia. The soils are of small extent.

MLRA OFFICE RESPONSIBLE: Morgantown, West Virginia

SERIES ESTABLISHED: Pulaski County, Virginia, 1979.

REMARKS: Diagnostic horizons and features recognized in this pedon are:
Orchric Epipedon: The surface from 0 to 9 inches (the Ap horizon).
Argillic horizon: The horizons between 26 and 75 inches (the Bt1, Bt2 and the 2Bt3 horizons).
Palic: Clay does not decrease by 20 percent in the solum.

National Cooperative Soil Survey
U.S.A.

http://ortho.ftw.nrcs.usda.gov/osd/dat/S/SLABTOWN.html

Appendix B: Initial Site Characterization Soil Analyses

Particle Size Analysis

Pre-Plot Preparation Soil Samples

June 13, 2007

County: Rachel
Date: 6/27/2007

Fraction*	VCS	CS	MS	FS	VFS	CSI	MSI	FSI	C
Size (mm)	1.000-2.000	0.500-1.000	0.250-0.500	0.100-0.250	0.050-0.100	0.020-0.050	0.005-0.020	0.002-0.005	<0.002
Sieve #	18	35	60	140	325	---	---	---	---

Sample Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Data ID#					Rachel	Rachel	Rachel	Rachel	Rachel	Rachel	Rachel	Rachel	Rachel	Rachel	Rachel	Rachel
Lab #					1A	1B	2A	2B	3A	3B	4A	4B	5A	5B	6A	6B
Series																
Horizon																
Depth																
%VCS					1.9	1.6	2.1	2.1	3.6	1.8	1.9	2.0	2.9	2.7	2.9	2.4
%CS					5.8	4.9	6.1	5.0	6.8	5.4	5.1	5.2	6.2	6.1	7.5	6.6
%MS					14.9	12.4	15.0	12.6	16.9	13.2	14.7	12.8	13.4	12.1	14.6	12.9
%FS					17.7	16.4	17.9	14.3	17.5	18.4	18.5	16.0	14.2	14.4	16.6	13.6
%VFS					8.3	9.2	7.6	10.3	8.7	9.1	8.9	8.6	6.7	9.0	7.9	10.9
Total % Sand					48.6	44.5	48.8	44.3	53.5	48.0	49.2	44.6	43.5	44.3	49.6	46.4
%CSI					11.9	11.2	12.1	12.2	9.2	12.4	10.3	11.5	12.6	12.7	15.2	14.8
%MSI					18.2	18.0	17.7	17.4	18.6	17.9	19.4	17.8	22.8	21.5	19.9	19.2
%FSI					9.1	8.6	7.9	7.7	8.0	7.9	9.6	8.4	10.1	8.6	10.2	10.3
Total % Silt					39.2	37.7	37.7	37.3	35.9	38.2	39.3	37.7	45.5	42.8	45.4	44.2
Total % Clay					12.2	17.8	13.5	18.4	10.6	13.8	11.6	17.7	11.0	12.9	5.0	9.4
Textural Class					L	L	L	L	SL	L	L	L	L	L	SL	L

Plot #

Between plots 1 & 2

Between plots 5 & 6

Plot 10

Between plots 14 & 15

Between plots 18 & 19

Between plots 22 & 23

Appendix C: Soil Profiles by Dr. Daniels

RACHEL LAYMAN + LEE DANIELS 10/2/07

Soil Profile SOIL REHAB #1 **Description Worksheet** (reference Field Book for Describing Soils or Soil Profile Desc. Manual)

Horizon			Depth	Texture		Color			Redoximorphic Features (1 or 2 of each)					Structure		Consis-tence	Fine + V. F. Roots
#	% *	Name*	Bottom in cm	Rock Modi-fier	Fine-earth Class*	Moist Matrix*			Fe Depletions		Fe Concentrations		Linings or masses?	Grade	Shape	Moist	Abun-dance
						Hue	Val	Chr	% vol.	Full Color Hue V/C	% vol.	Full Color Hue V/C					
1		Ap	0-9			10YR	4	3						1 F&M	9R+SBK	FR	
2		BAt?	9-15			10YR	5/5	4/6 ↓						1 F&M	SBK	FR	
3		Bt1	15-32			5YR	5	8			2%	BLK MN CONCS		2 M	SBK	FR	
4		Bt2	32-60+			2.5YR	4	8						1/2 M	SBK	FR	
5																	
6																	
7																	
8																	
Pg																	

Additional Description Worksheet (reference Field Book for Describing Soils or Soil Profile Desc. Manual)

Horizon		Rock fragments				Mn Concentrations		Clay Films	Sandy or leached pockets	Rock-controlled structure?	Brittle?	Perching layer?	Root-limiting?
Hor #	Name	Gravel**	Cobbles**	Stones	Bldrs	Concre-tions	Films + masses						
				%	%	%	%	y/n	% vol	% vol	% vol	y/n	y/n
1													
2													
3													
4													
5													
6													
7													
8													
Page#													

* If 2 major non-redox colors in the same horizon, split the boxes and give a vol. percentage of each. Also split if 2 separate horizon materials like E/A, E/Bt, or Bt/E.

** Channers are flattened gravels and cobble-sized rocks. Comments:

RACHEL LAYMAN + LEE DANIELS

10/2/07

Soil Profile SOIL REHAB #2 - SLABTOWN **Description Worksheet** (reference Field Book for Describing Soils or Soil Profile Desc. Manual)

Horizon #	Horizon % *	Horizon Name*	Depth Bottom IN ~~cm~~	Texture Rock Modi-fier	Texture Fine-earth Class*	Color Moist Matrix* Hue	Color Moist Matrix* Val	Color Moist Matrix* Chr	Redoximorphic Features (1 or 2 of each) Fe Depletions % vol.	Fe Depletions Full Color Hue V/C	Fe Concentrations % vol.	Fe Concentrations Full Color Hue V/C	Linings or masses?	Structure Grade	Structure Shape	Consis-tence Moist	Fine + V. F. Roots Abun-dance
1		Ap	0-9			10YR	4	3								VFR	
2		AB	9-15			10YR	5	4						1 Fn M	GR + SBk	FR	
3		Bt1	15-24			10YR	5	6			2	blk mn concs 2-4mm		1 M	SBk	FR	
4		Bt2	24-48			7.5YR	5	6	20 10	10YR 5/3 10YR 6/3				1 M	SBk	FR	
5		Bt3	48-60+			7.5YR	5	8	30 10	7.5YR 6/6 10YR 7/3				1 F/M	SBk	FR	
6																	
7																	
8																	
Pg																	

Additional Description Worksheet (reference Field Book for Describing Soils or Soil Profile Desc. Manual)

Horizon Hor #	Horizon Name	Rock fragments Gravel**	Rock fragments Cobbles**	Rock fragments Stones	Rock fragments Bldrs	Mn Concentrations Concre-tions	Mn Concentrations Films + masses	Clay Films	Sandy or leached pockets	Rock-controlled structure?	Brittle?	Perching layer?	Root-limiting?
				%	%	%	%	y/n	% vol	% vol	% vol	y/n	y/n
1													
2													
3													
4													
5													
6													
7													
8													
Page#													

* If 2 major non-redox colors in the same horizon, split the boxes and give a vol. percentage of each. Also split if 2 separate horizon materials like E/A, E/Bt, or Bt/E.

** Channers are flattened gravels and cobble-sized rocks. Comments:

Appendix D: Profile Samples Soil Analyses

Samples collected by Lee Daniels

App 1

Particle Size Analysis

County: Layman
Date: 10/19/07

Fraction*
Size (mm)
Sieve #

Sample Number	1	2	3	4	5	6	7
Data ID#	Layman	Layman	Layman	Layman	Layman	Layman	Layman
Lab #	Rehab 1	Rehab 1	Rehab 1	Rehab 1	Rehab 2	Rehab 2	Rehab 2
Series	Ap	AB	Bt1	Bt2	Ap	AB	Bt1
Horizon							
Depth							
%VCS	1.8	1.7	0.9	0.8	3.2	3.8	3.0
%CS	4.9	5.6	3.4	3.6	6.2	6.9	6.2
%MS	15.4	12.7	11.5	11.1	11.5	11.3	10.6
%FS	17.9	16.8	15.2	14.8	13.3	12.6	12.7
%VFS	4.3	8.2	7.8	7.5	7.8	8.6	8.0
Total % Sand	44.3	45.0	38.9	37.7	42.0	43.2	40.5
%CSI	14.3	9.5	9.1	7.2	11.1	10.0	8.9
%MSI	19.9	20.7	15.7	9.6	23.6	23.2	22.7
%FSI	8.2	8.4	5.7	2.6	8.5	9.0	8.8
Total % Silt	42.4	38.6	30.5	19.4	43.2	42.2	40.4
Total % Clay	13.4	16.3	30.7	42.9	14.8	14.6	19.1
Textural Class	L	L	CL	C	L	L	L

VCS	CS	MS	FS	VFS	CSI	MSI	FSI	C
1.000-2.000	0.500-1.000	0.250-0.500	0.100-0.250	0.050-0.100	0.020-0.050	0.005-0.020	0.002-0.005	<0.002
18	35	60	140	325	---	---	---	---

8	9	10	11	12	13	14	15	16
Layman	Layman							
Rehab 2	Rehab 2							
Bt2	Bt3							

3.8	3.5							
6.2	6.3							
11.2	12.1							
9.7	13.4							
11.1	8.5							
42.0	43.8							

10.4	9.7							
19.6	17.4							
6.3	7.1							
36.3	34.1							

21.7	22.0							

L	L							

Rachel Layman
Rehab

10/18/2007

Total C and N

Sample Name	Horizon	Sample Weight	% N	% C	C:N Ratio
Rehab 1	Ap	1000.80	0.1345	1.3572	10.09
Rehab 1	AB	1002.80	0.0377	0.3903	10.34
Rehab 1	Bt1	1010.60	0.0226	0.1455	6.44
Rehab 1	Bt2	1013.00	0.0243	0.1361	5.59
Rehab 2	Ap	1008.10	0.1265	1.3323	10.56
Rehab 2	AB	1008.70	0.0320	0.3576	11.22
Rehab 2	Bt1	1017.70	0.0188	0.1590	8.45
Rehab 2	Bt2	1010.60	0.0272	0.2296	8.44
Rehab 2	Bt3	1011.80	0.0172	0.1425	8.26

Rachel Layman
Rehab

10/18/2007

Nutrient Analysis

				%									mg/100g	%				
Sample Name	Horizon	pH	BpH	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B	Est. CEC	Acidity	Base Sat	Ca Sat.	Mg Sat	K Sat
Rehab 1	Ap	5.76	6.24	2	95	532	86	1.4	20.1	0.2	7.4	0.1	4.6	79.2	58.3	15.5	15.5	5.3
Rehab 1	AB	6.22	6.39	2	105	335	85	0.6	12	0.3	7.7	0.1	2.7	97.8	61.9	25.9	25.9	9.9
Rehab 1	Bt1	5.64	6.24	2	123	356	130	0.4	2.5	0.2	9.1	0.3	4.1	76.9	43.2	26	26	7.7
Rehab 1	Bt2	5.75	6.32	2	50	333	154	0.3	0.6	0.2	7.1	0.1	3.5	86.5	47.1	35.8	35.8	3.6
Rehab 2	Ap	5.51	6.17	2	75	412	83	1.2	24.4	0.3	9.5	0.1	4.3	68.2	47.9	15.8	15.8	4.4
Rehab 2	AB	5.80	6.39	2	79	228	58	0.5	13.2	0.3	10.7	0.2	1.9	96.8	60.6	25.5	25.5	10.7
Rehab 2	Bt1	5.61	6.27	2	65	312	111	0.4	6.5	0.3	12.4	0.2	3.4	77.3	45.6	26.8	26.8	4.8
Rehab 2	Bt2	5.82	6.34	2	98	376	109	0.6	7.1	0.3	10.6	0.1	3.4	89.4	55.5	26.6	26.6	7.4
Rehab 2	Bt3	5.65	6.29	2	67	341	88	0.3	4.6	0.3	9.2	0.1	3.2	79.9	52.3	22.3	22.3	5.3

Appendix E: VCE Analytical Methods

Laboratory Procedures: Virginia Tech Soil Testing Laboratory

Publication No. 452-881

Source: http://pubs.ext.vt.edu/452/452-881/452-881.html

Gregory L. Mullins, Extension Nutrient Management Specialist, Virginia Tech; Steven E. Heckendorn, Manager, Soil Testing Laboratory, Virginia Tech.

Table of Contents

Introduction

The procedures for soil analysis used in the Soil Testing Laboratory were established in the early 1950s*. Although the chemical principles have not changed, procedures have been revised over the years to utilize advances in instrumentation which allow more accurate and rapid chemical determinations.

A routine test, consisting of eleven separate analyses, is performed on all samples. In addition, two separate tests are offered on a request basis. These tests are applicable only under certain conditions for which research and calibration work has been conducted. The routine and special tests consist of the following:

Routine Test

water pH (WpH)

buffer pH (BpH)

phosphorus (P)

potassium (K)

calcium (Ca)

magnesium (Mg)

zinc (Zn)

manganese (Mn)

copper (Cu)

iron (Fe)

boron (B)

Special Tests

soluble salts
organic matter

*Rich, C.I., 1955. Rapid soil testing procedures used at Virginia Polytechnic Institute. Virginia Agriculture Experiment Station. Bull. 475, p. 8.

Sample Preparation

Soil samples arrive in 1/2-pint cardboard cartons. Generally, Soil Sample Information Sheets (SSIS) are packaged with the samples. The cartons are opened in a separate preparation area and placed in drying trays. Twenty-eight unknown samples plus two control samples are placed in each drying tray. The two control samples are one known internal reference sample and either a blank or replicate sample. At this time, each sample is assigned a laboratory number which, along with the year, is stamped on the SSIS. The samples are numbered consecutively each calendar year, beginning with 1 on January 1.

The trays of samples are placed in a cross-flow forced-air drying cabinet through which room-temperature filtered air is drawn. The air can be heated 5° to 8°C above the ambient temperature for drying extremely wet samples. Samples remain in the drying cabinet overnight or until air dry.

Air-dried (at 20° to 40°C) samples are crushed with a hammermill-type crushing machine and passed through a 10-mesh (2-mm opening) stainless steel sieve. The samples are then returned to the original sample boxes until the various subsamples are measured out.

Water pH (WpH) Determination

Buffer Solutions: Color-coded buffer solutions of pH 4.0, 7.0, and 10.0 are purchased from commercial sources.

Electrode Internal Filling Solution: Use Thermo Orion's 3M KCl, (with no silver), Ross™ Sure-Flow® Internal Filling Solution, Cat. No. 810007.

Electrode Soaking Solution: Use 5 g of KCl in a liter of pH 7 buffer solution.

Procedure:
Daily, do a two-point calibration of the pH meter using fresh buffer solutions of pH 4 and 7, and recheck the calibration before starting every batch of samples.

Scoop 10 cm^3 of soil from the prepared sample into a 50 ml beaker. With an automatic pipetting machine add 10 ml of distilled water for a 1:1 (vol/vol) ratio. Thoroughly mix the solution with a glass/plastic rod or mechanical stirrer and allow it to sit for a minimum of 10 minutes and a maximum of 2 hours.

The automated pH analyzer is set to stir solutions for a 5-second equilibration delay before starting to take pH readings. It then continues to stir the soil suspension while the software waits for 10 readings to be stable within 0.02 pH units. Probes are automatically washed after a pH reading greater than 8.0 or less than 4.0. Readings are electronically recorded to the 0.01 pH unit. The pH readings of quality-control samples are manually checked before uploading the sample data to verify that they are within ±0.1 pH unit of the expected value. This includes
reading a pH 10 buffer solution if a sample had a pH reading above 7.00. After use, place the electrodes in the soaking solution.

Notes:

For fine-textured soils containing a high level of organic matter, it may be necessary to add an additional 10 ml of distilled water to make a suspension.
The TPS pH meter has a temperature sensor for automatic temperature compensation (ATC). This ATC probe should sit in a flask of ambient temperature water within the LabFit pH Analyser next to the soil samples being measured.
If a pH probe's reading becomes sluggish, unstable, or not reproducible (possibly indicating that the liquid reference junction has become clogged), depress the electrode's top cap to flush the junction.

Buffer pH (BpH) Determination

Mehlich Buffer Preparation:
Using a 4-liter volumetric flask, add:

~ 2 liters of distilled water (DW);

10 ml of glacial acetic acid, CH3COOH, 99.5%, 17.4N;

39 ml of 50% triethanolamine (1 TEA : 1 DW);

72.0 g of sodium glycerophosphate, hydrate, $C_3H_5(OH)_2PO_4Na_2 \cdot xH_2O$,FW=216.04(anhy.); or 1,2,3-Propanetiol mono (dihydrogen phosphate) disodium salt, $(HOCH_2)_2CHOPO_3Na_2$; or Glycerol phosphate Disodium salt Hydrate,$C_3H_7O_6PNa_2$, CAS #: 154804-51-0 {Sigma's 1 kg, G6501 or Gallard-Schlesinger's 50 kg GSODGLYERO via Doe & Ingalls};

172.0 g of ammonium chloride (NH_4Cl);

48.0 g of calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$); {or alternatively use 80.0 g $BaCl_2 \cdot 2H_2O$ }.

Stir using a stir-bar and stir-plate until all salts are dissolved and allow the solution to warm up to room temperature.

Bring to the 4-liter volume with distilled water.

Adjust to pH 6.60 ±0.04 when diluted 1:1 with distilled water. Use drops of acetic acid to lower the pH or drops of 1:1 aqueous TEA to raise the pH.

Use an acid standard to check the preparation of the buffer mixture as follows: combine 10 ml of buffer, 10 ml of distilled water, and 10 ml of commercially prepared 0.05N HCl solution. This mixture should drop the initial buffer pH by 1.35±0.1 units. If the pH is not within these limits, check the preparation of the buffer reagent to make
certain that all ingredients were added properly.

Make only what will be needed for a week to prevent microbial growth in storage. When calcium chloride is used instead of barium chloride, containers and dispensers may need to be disinfected with dilute (10%) chlorine bleach (sodium hypochlorite) between batches of solution. Rinse very well with distilled water.

Procedure:
On samples with a WpH ≤6.94, add 10 ±0.2 ml of the Mehlich buffer solution using the 1:1 (vol/vol) soil-water mix from the water pH determination. Thoroughly mix the solution with a glass/plastic rod and allow it to sit for a minimum of 30 minutes. Stir the solution again immediately before reading and while the pH probe is equilibrating in the soil suspension. Record the first stable pH reading to the nearest 0.01 unit. Verify calibration of pH electrodes before measuring buffer pH'fs. Check the pH of the buffer solution on the daily blank sample. A rise in its pH indicates fungal growth in the buffer.

Return to Table of Contents

Determination of P, K, Ca, Mg, Zn, Mn, Cu, Fe, B, and Al

Extracting Solution (Mehlich 1, 0.05N HCl in 0.025N H_2SO_4):
Measure approximately 15 liters of distilled water into a 20-liter plastic container. Add 14.0 ml of concentrated sulfuric acid (H_2SO_4), 82.0 ml of concentrated hydrochloric acid (HCl), and distilled water to make a 20-liter volume and mix thoroughly.

Extraction Procedure:
Measure one 4-cm^3 scoop of soil into a 60-ml straight-walled plastic extracting beaker, and add 20 ml of the Mehlich 1 extracting solution with an automatic pipetting machine. The samples are shaken on a reciprocating shaker with a stroke length of 3.8 cm for 5 minutes at 180 oscillations per minute and filtered through Whatman No. 2 (or equivalent), 11-cm filter paper soon after the shaking stops.

Analysis Procedure:
All elements are analyzed in the same extract by an ICP (inductively coupled plasma atomic emission spectrometer). Transfer filtrate from the extraction beaker to an ICP autosampler cup by using a disposable

polyethylene pipette. The transfer is a two-step procedure with the first aliquot being a rinse and the second aliquot for the actual transfer. Pipette 4 ml of filtrate and discard into a waste beaker. Pipette another 4 ml of the same filtrate into the autosampler rack's polystyrene sample cups. Once all sample filtrates have been transferred, cover the autosampler rack with plastic wrap to prevent air-borne contaminants (dust, lint, etc.) from getting into the solutions. This is important to prevent ICP nebulizer clogging and contamination. Samples may be stored overnight by covering them with plastic wrap, parafilm, or capping and placing them in a refrigerator. After refrigeration, allow the samples to equilibrate to room temperature before ICP analysis.

Elemental Analysis by ICP:
The ICAP 61E (a simultaneous spectrometer), equipped with a Thermo Elemental autosampler, is set up to analyze approximately 30 samples for 10 elements about every 25 minutes (an 11-second rinse [during exposure time] followed by a 25-second flush time and one 5-second sample exposure with one 5-second background exposure). Read and verify a quality control solution after every tray of 30 samples.

ICP Working Standards:
The ICP is calibrated with the following series of standards (Note: atomic absorption standards are not sufficiently pure for ICP standards; use only spectrally pure, plasma-quality standards).

Soil #1: Final solution concentration: 0.05 *N* HCl and 0.025 *N* H_2SO_4.

Use the Mehlich 1 (M1) extracting solution or to approximately 250 ml of deionized water in a half-liter volumetric flask, add 2 ml of concentrated reagent grade HCl, and 0.35 ml of concentrated reagent grade H_2SO_4, dilute to volume with deionized water and mix well.

Soil #2: Final elemental concentration in solution: 30 µg ml^{-1} P, 2 µg ml^{-1} Zn, 2 µg ml^{-1} B.

To approximately 250 ml of M1 extracting solution in a half-liter volumetric flask, add 15 ml of 1000 µg ml^{-1} P calibration standard, 1 ml of 1000 µg ml^{-1} Zn calibration standard, 1 ml of 1000 µg ml^{-1} B calibration standard and dilute to volume with extracting solution and mix.

Soil #3: Final elemental concentration in solution: 300 µg ml^{-1} Ca, 100 µg ml^{-1} K, 50 µg ml^{-1} Mg, 10 µg ml^{-1} Al, 10 µg ml^{-1} Mn.

Add to a half-liter volumetric flask with approximately 250 ml of M1 extracting solution 15 ml of 10,000 µg ml^{-1} Ca calibration standard, 5 ml of 10,000 µg ml^{-1} K calibration standard, 2.5 ml of 10,000 µg ml^{-1} Mg calibration standard, 5 ml of 1,000 µg ml^{-1} Al calibration standard, and 5 ml of 1000 µg ml^{-1} Mn calibration standard; dilute to volume with extracting solution and mix.

Soil #4: Final elemental concentration in solution: 10 µg ml^{-1} Cu, 25 µg ml^{-1} Fe.

Add to a half-liter volumetric flask with approximately 250 ml of M1 extracting solution 5 ml of 1000 µg ml^{-1} Cu calibration standard and 12.5 ml of 1000 µg ml^{-1} Fe calibration standard; dilute to volume with extracting solution and mix.

ICP Quality Control Standard:
The quality control solution is prepared with spectrally pure, ICP-quality, calibration stock solutions. (Note: For the elements P, K, Ca, and Mg, use standard stock solutions from a manufacturing source other than the one used to prepare the working standards.) Add to a half-liter volumetric flask with approximately 250 ml of Mehlich 1 extracting solution the following amounts of each stock solution then dilute to volume with extracting solution and mix well:

Element	Final Concentration µg ml^{-1}	High Purity Reference Solution
P	10	5 ml of 1,000 µg ml^{-1}
K	25	1.25 ml of 10,000 µg ml^{-1}
Ca	200	10 ml of 10,000 µg ml^{-1}
Mg	20	1 ml of 10,000 µg ml^{-1}
Zn	1	0.5 ml of 1,000 µg ml^{-1}
Mn	1	0.5 ml of 1,000 µg ml^{-1}
Cu	1	0.5 ml of 1,000 µg ml^{-1}

Fe	5	2.5 ml of 1,000 µg ml^{-1}
B	1	0.5 of 1,000 µg ml^{-1}

Calculation of Elemental Concentrations

For each element, the calculation for ppm in soil is as follows:

ppm in solution x 5 = ppm in soil on a volume basis (mg/dm3)

ppm in solution x 4 = ppm in soil on a weight basis (mg/kg)

where 4 is the dilution factor assuming a soil scoop density of 1.25 g/cm3.

To convert from ppm (wt. basis) to lbs/acre the equation is:

ppm in soil x 2 = lbs/acre

where weight of an acre furrow slice (6 2/3-inch depth) is assumed to be 2 million pounds.

Estimation of Effective CEC by Summation

Theory:
The Cation Exchange Capacity (CEC) can be reasonably estimated by summation of the Mehlich 1 extractable bases, or non-acid generating cations (Ca, Mg and K), plus the exchangeable acidity estimated from the Mehlich buffer pH after conversion of all analytical results to meq/100 cm3 or cmol(+)/kg

This calculated method is closer to a measured Effective CEC, which is measured at the present pH of the soil, than it is to the soil's potential CEC, which is measured in solutions buffered at pH 7.0 or higher.

This method is inappropriate for soils with a high soluble salts level or for alkaline soils because these soils may be over-fertilized, calcareous, gypsiferous, or relatively unweathered and could result in an erroneously high CEC value by the release of nonexchangeable cations.

Calculation:
Estimated Soil E-CEC = Acidity + Ca + Mg + K (in the units of meq/100 g soil or cmol/kg)

Acidity (meq/100 g of soil) = 37.94 - (5.928 x BpH) where BpH = Mehlich buffer pH reading for an individual soil sample.

meq Ca/100 g = lb Ca per Acre ÷ 401

meq Mg/100 g = lb Mg per Acre ÷ 243

meq K/100 g = lb K per Acre ÷ 782

Return to Table of Contents

Soluble Salts

Conductivity Standard:
Use a commercially prepared NIST traceable conductivity standard of 1,000 or 1,420 µsiemens/cm.

or

Prepare potassium chloride standard solution (0.01 N KCl): Dissolve 0.7456 g of potassium chloride (KCl) in deionized water in a 1-liter volumetric flask. Mix well and dilute to volume. The conductivity of this solution at 25°C is 1,412 µsiemens/cm.

Procedure:
Measure one 20-cm^3 scoop of soil into a 50-ml beaker, add 40 ml of distilled water for a soil:water ratio of 1:2 (vol/vol). Include at least one internal soil reference ("test") sample per batch of unknown soil samples. Stir the solution and allow the suspension to settle for at least 1 hour. Check the conductivity meter's calibration against the conductivity standard. At 25°C, the standard has an electrical conductivity of 1.00 or 1.41 mmho/cm (or mS/cm). Set the meter in the Temperature Compensation Conductivity mode, and cell constant (C) to 1.00/cm. The electrical conductivity (EC) of the supernatant liquid of the soil-water solution is determined with the meter set on the µS/cm scale. Record the EC as one tenth of the meter's reading, (move the decimal one place to the left on the meter's display), in order to give the results in mhos x 10^{-5} units. The ppm soluble salts in the soil are calculated from the following equation:

$$\text{ppm soluble salts in soil} = EC \times 6.4 \times 2$$

In this equation, EC represents the conductivity reading in mhos x 10^{-5}, 6.4 is the factor for converting the conductivity measurement to ppm soluble salts, and 2 represents the water volume dilution factor. Report as ppm soluble salts in soil.

Useful Equations:
EC (mho x 10^{-5}/cm) / 100 = mmho/cm

ppm (mg salt/liter) / 1280 = mmho/cm

0.1 S/m = 1 dS/m = 1 mS/cm = 1 mmho/cm

Resistance of a solution is the reciprocal of the electrical conductivity; therefore,

0.1 µmho = 10.0 Mohm.

Return to Table of Contents

Soil Organic Matter (SOM) by Walkley-Black (WB)

Reagent A: Sodium dichromate solution (0.67M): Dissolve 500 g of reagent grade sodium dichromate ($Na_2Cr_2O_7 \cdot 2H_2O$) in tap water to a volume of 2 1/2 liters.
Reagent B: Concentrated reagent grade sulfuric acid (H_2SO_4).

Procedure:
The procedure is a modified Walkley-Black method. Measure one 1.5-cm^3 scoop of soil into a 200-ml test tube. Under a hood, add 20 ml of Reagent A to the soil followed by 20 ml of Reagent B. Allow the solution to cool at least 40 minutes. After cooling, add 100 ml of tap water, mix the solution, and allow to stand overnight (or at least 8 hours). After incubation, withdraw an aliquot of the supernatant using a syringe-type pipette and transfer it to a colorimeter vial. Take readings using a colorimeter set to a 645 nm wavelength. The percentage of organic matter is determined by reference to Table 2.

Table 2. Colorimeter readings and percent organic matter.

Colorimeter Reading	Organic Matter, %	Colorimeter Reading	Organic Matter, %	Colorimeter Reading	Organic Matter, %
100	0.0	57	2.8	29	6.7
99-95	0.1	56	2.9	28	6.9
94-91	0.2	55	3.0	27	7.1
90-89	0.3	54	3.1	26	7.3
88-87	0.4	53	3.2	25	7.5
86	0.5	52	3.3	24	7.7
85-84	0.6	51	3.4	23	7.9
83	0.7	50	3.5	22	8.1
82-81	0.8	49	3.6	21	8.4

80	0.9	48	3.7	20	8.8
79-78	1.1	47	3.8	19	9.1
77	1.1	46	3.9	18	9.5
76-75	1.2	45	4.0	17	9.8
74	1.3	44	4.1	16	10.2
73-72	1.4	43	4.2	15	10.5
71	1.5	42	4.3	14	10.9
70-69	1.6	41	4.4	13	11.2
68	1.7	40	4.5	12	11.6
67	1.8	39	4.7	11	11.9
66	1.9	38	4.9	10	12.3
65	2.0	37	5.1	9	12.6
64	2.1	36	5.3	8	13.0
63	2.2	35	5.5	7	13.3

62	2.3	34	5.7	6	14.1
61	2.4	33	5.9	5	15.0
60	2.5	32	6.1	4	15.0
59	2.6	31	6.3	3	15.0
58	2.7	30	6.5	2-1	15.0

Soil Organic Matter (SOM) by Weight Loss On Ignition (LOI)

Procedure:
Tare balance and weigh 50-mL beakers. Scoop 5 cm^3 of air-dried, 2-mm sieved soil into a beaker. Dry for a minimum of two hours at 150°C ±5°C. Maintain at 100°C until weighing. Record the weight of the beaker plus the warm soil sample to ±1 mg. Heat at 360°C for two hours after the temperature reaches 360°C ±5°C. Cool to 105°C and maintain at 105°C until weighing. Weigh the beaker and warm ash in a draft-free environment to ±1 mg. Calculate and report %LOI as percent organic matter to the nearest tenth of a percent.

Calculations:
Dried Soil ($Soil_d$) = (Wt of Beaker + Wt of Soil at 150°C) - Wt of Beaker

Ashed Soil ($Soil_a$) = (Wt of Beaker + Wt of Soil at 360°C) - Wt of Beaker

Percent weight loss on ignition (%LOI):

$$\%LOI = \frac{Soil_d - Soil_a}{Soil_d} \times 100$$

Note:
The LOI (a gravimetric, dry oxidation) method is used to estimate the soil organic matter content for all samples except for those coming from commercial farmland in the Piedmont counties of Virginia. The Walkley-Black (a wet, chemical oxidation) method is used in those cases, due to the presence of gibbsite

(Al_2O_3 • $3H_2O$) in the clay fraction of soil material in that area of the state. Gibbsite has been reported to lose substantial amounts of water at around 300°C.

Return to Table of Contents

Instruments for Soil Analyses

Analysis	Instrument
Soil Drying	Cross-flow forced-air soil drying cabinet, developed at Virginia Tech
Soil Grinding	Custom Lab Equipment DC-1 HD Dynacrush
pH Auto-analyzer	LabFit Pty Ltd, model AS-3000 Automated Dual pH Analyser
pH Meter	TPS Pty Ltd, model WP-80D, Dual pH-mV and temp. meter
pH Electrode	Thermo Orion model 8165BNWP, RossTM combination pH electrode, Sure-Flow®, with epoxybody and BNC connector
Nutrient Extraction	Eberbach Reciprocating, Variable Speed Shaker No. 6000
Elemental Analysis of P, K, Ca, Mg, Zn, Mn, Cu, Fe, B &	Thermo Elemental ICAP 61E (Inductively Coupled Argon Plasma Atomic Emission Simultaneous Spectrometer) using

Al	Thermo's ICP Manager 61 software, and equipped with a TJA-300 autosampler.
Soluble Salts	YSI 3100 Conductivity Instrument with a YSI 3254 Pyrex 5-ml Fill Cell
Organic Matter - WB	Spectronic® 20 Genesys™ Colorimeter
Organic Matter - LOI	Blue M Electric High Temperature (up to 704°C), Ultra-Temp, forced-air drying oven, model CW-6680F, with Pro 550 microprocessor-based controller.
Organic Matter - LOI	PG503-SDR Mettler Toledo (MT) analytical balance controlled by MT's BalanceLink software (v2.20).

ICP Parameters

The ICP is housed in an instrument room maintained at 21°C (70°F) ± 1°C (2°F). Swings in both temperature and humidity can affect the analytical results. To enhance precision the solutions are introduced to a cross flow nebulizer with a peristaltic pump. The ICP is profiled using a Hg wavelength.

The following analytical lines are used:

Element	Wavelength (nm)	Physical Channel Number	Analytical Range ($\mu g\ ml^{-1}$)

P	214.914	38	0.06 - 1000
K	766.490	24	0.3 - 1000
Ca	373.690	43	0.1 - 1500
Mg	279.079	14	0.01 - 350
Zn	213.856	33	0.004 - 150
Mn	257.610	37	0.001 -150
Cu	324.754	4	0.002 - 150
Fe	259.940	12	0.005 - 150
B	249.678	11	0.006 - 150
S	182.04	7	0.1 - 500
Na	588.995	16	0.01 - 200

Li	670.784	20	0.006 - 150
Al	396.153	41	0.025 - 500
Al	308.215	17	1.0 - 5000
Hg	546.074	13	Monitor

References

Sample Preparation:

Gelderman, R.H., and A.P. Mallarino. 1998. Soil Sample Preparation. p. 5-6. In Brown, J.R. (ed.). Recommended Chemical Soil Test Procedures for the North Central Region. North Central Regional Research Publication Bull. No. 221 (revised). Missouri Agricultural Experiment Station SB 1001, University of Missouri, Columbia, Mo.

Hoskins, B. and D. Ross. 1995. Soil Sample Preparation and Extraction. p. 3-10. In Sims, J.T. and A.M. Wolf (ed.). Recommended Soil Testing Procedures for the Northeastern United States. Northeastern Regional Pub. No. 493 (2nd edition). Agricultural Experiment Station University of Delaware, Newark, Del.

pH:

Kalra, Y.P. 1995. Determination of pH of soils by different methods: collaborative study. *Journal of the Association Off. Analytical Chemistry International* 78(2):310-321.

Mehlich, A. 1976. New Buffer pH Method for Rapid Estimation of Exchangeable Acidity and Lime Requirement of Soils. 7(7):637-653.

Soil Analysis Handbook of Reference Methods. 1999. Buffer pH and Lime Requirement. p. 41-55. Soil and Plant Analysis Council, Inc., Athens, Ga.

Soil Analysis Handbook of Reference Methods. 1999. Soil pH, and Exchangeable Acidity and Aluminum. p. 27-39. Soil and Plant Analysis Council, Inc., Athens, Ga.

Phosphorus:

Kuo, S. 1996. Phosphorus. p. 869-919. In D.L. Sparks (ed.) *Methods of Soil Analysis. Part 3. Chemical Methods*. Soil Science Society of America Book Ser. 5. SSSA and ASA, Madison, Wis.

Murphy, J. and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta.* 27:31-36.

Soil Analysis Handbook of Reference Methods. 1999. Phosphorus. p. 69-91. Soil and Plant Analysis Council, Inc., Athens, Ga.

Potassium, Calcium, Magnesium:
Mehlich, A. 1953. Determination of P, Ca, Mg, K, Na, and NH4. North Carolina Soil Test Division (Mimeo. 1953).

Soil Analysis Handbook of Reference Methods. 1999. Major Cations. p. 93-115. Soil and Plant Analysis Council, Inc., Athens, Ga.

Zinc:
Alley, M.M., D.C. Martens, M.G. Schnappinger, Jr., and G.W. Hawkins. 1972. Field calibration of soil tests for available zinc. *Soil Science Society of America Proceedings* 36:621-624.

Manganese:
Cox, F. R. 1968. Development of a yield response prediction and manganese soil test interpretation for soybeans. *Agronomy Journal* 60:521-524.

Organic Matter:
Combs, S.M. and M.V. Nathan. 1998. Soil Organic Matter. p. 53-58. In Brown, J.R. (ed.) Recommended Chemical Soil Test Procedures for the North Central Region. North Central Regional Research Publication Bull. No. 221 (revised). Missouri Agricultural Experiment Station SB 1001, Univ. of Missouri, Columbia, Mo.

Method 2.7.08. Chapter 2. p. 37. In MCuniff, P.A. (ed). *Official Methods of Analysis of AOAC International*, 16th edition. AOAC, Inc., Arlington, Va.

Nelson, D.W., and L.E. Sommers. 1996. Total Carbon, Organic Carbon, and Organic Matter. p. 961-1010. In D.L. Sparks (ed.) *Methods of Soil Analysis. Part 3. Chemical Methods*. Soil Science Society of America Book Ser. 5. SSSA and ASA, Madison, Wis.

Peech, M., L.T. Alexander, L.A. Dean, and J. Fielding Reed. 1947. Methods of soil analysis for soil-fertility investigations. USDA Circ. 757, p. 5-7.

Schulte, E.E. 1995. Recommended Soil Organic Matter Tests. p. 52-60. In Sims, J.T. and A.M. Wolf (ed.). *Recommended Soil Testing Procedures for the Northeastern United States*. Northeastern Regional Pub. No. 493 (2nd edition). Agricultural Experiment Station Univ. of Delaware, Newark, Del.

Schulte, E.E. and B.G. Hopkins. 1996. Estimation of Soil Organic Matter by Weight Loss-On-Ignition. p. 21-31. In Magdoff, F.R., M.A Tabatasbai, and E.A. Hanlon, Jr. (ed.) *Soil Organic Matter: Analysis and Interpretation*. SSSA, Inc., Madison, Wis. Special Pub. No. 46; Proceedings of a symposium sponsored by Divisions S-4 and S-8 of the Soil Science Society of America in Seattle, Wash. 14 Nov. 1994.

Schulte, E.E., C. Kaufmann, and J.B. Peter. 1991. The influence of sample size and heating time on soil weight loss-on-ignition. *Comm. In Soil Science and Plant Analysis* 22(1-2):159-168.

CEC by Summation:
Hajek, B. F., F. Adams, and J. T. Cope. 1972. Rapid determination of exchangeable bases, acidity, and base saturation for soil characterization. *Soil Science Society of America Proceedings*. 36:436-438.

Isaac, Robert A., and William C. Johnson. 1984. *Methodology for the Analysis of Soil, Plant, Feed, Water and Fertilizer Samples* (revised). University of Georgia, Athens, Ga.

Sumner, M.E., and W.P. Miller. 1996. Cation Exchange Capacity and Exchange Coefficients. p. 1221-1222. In D. L. Sparks (ed.) *Methods of Soil Analysis. Part 3. Chemical Methods*. Soil Science Society of America Book Ser. 5. SSSA and ASA, Madison, Wis.

Warncke, D., and J.R. Brown. 1998. Potassium and Other Basic Cations. p. 33 . In Brown, J.R. (ed.) *Recommended Chemical Soil Test Procedures for the North Central Region*. North Central Regional Research Publication Bull. No. 221 (revised). Missouri Agricultural Experiment Station SB 1001, Univ. of Missouri, Columbia, Mo.

Wolf, Ann and Douglas Beegle. 1995. Recommended Soil Tests for Macronutrients: Phosphorus, Potassium, Calcium and Magnesium. Chapter 5. Cation Exchange Capacity section. p. 31. In Sims, J.T., and A.M. Wolf (ed.). Recommended Soil Testing Procedures for the Northeastern United States. Northeastern Regional Pub. No. 493 (2nd edition). Agricultural Experiment Station Univ. of Delaware, Newark, Del.

Soluble Salts:
Rhoades, J. D. 1996. Salinity: Electrical Conductivity and Total Dissolved Solids. p. 417-435. In D. L. Sparks (ed.) Methods of Soil Analysis. Soil Science Society of America Book Ser. 5 Part 3. Chemical Methods. SSSA and ASA, Madison, Wis.

Soil Analysis Handbook of Reference Methods. 1999. Conductance, Soluble Salts, and Sodicity. p. 57-67. Soil and Plant Analysis Council, Inc., Athens, Ga.

U.S. Salinity Laboratory Staff. 1954. Determination of the properties of saline and alkali soils. Chapter 2. p. 7-33 . In L. A. Richards (ed.) Diagnosis and improvement of saline and alkali soils. Agriculture Handbook No. 60. USDA-ARS.

Waters, W.E., W. Llewelyn, C.M. Geraldson, and S.S. Woltz. 1973. The interpretation of soluble salt procedures as influenced by salinity testing procedure and soil media. *Proceedings Tropical Region American Society of Horticulture Science*. 17:397-405.

Whitney D.A. 1998. Soil Salinity. p. 59-60. In Brown, J.R. (ed.) Recommended Chemical Soil Test Procedures for the North Central Region. North Central Regional Research Publication Bull. No. 221 (revised). Missouri Agricultural Experiment Station SB 1001, Univ. of Missouri, Columbia, Mo.

Instrumentation:
APHA-AWWA-WEF. 1998. *Standard Methods for the Examination of Water and Wastewater*. 20th ed. Section 3120, p. 3:37-43. In Clesceri, L.S., A.E. Greenberg, and A.D. Eaton (eds.) American Public Health Association, Washington, D.C.

Soil Analysis Handbook of Reference Methods. 1999. Methods of Instrumental Analysis. p. 207-224. Soil and Plant Analysis Council, Inc., Athens, Ga.

Soltanpour, P.N., G.W. Johnson, S.M. Workman, J.B. Jones Jr., and R.O. Miller. 1996. *Inductively Coupled Plasma Emission Spectrometry*. p. 91-139. In D.L. Sparks (ed.) *Methods of Soil Analysis. Part 3. Chemical Methods*. Soil Science Society of America Book Ser. 5. SSSA and ASA, Madison, Wis.

Walsh, L. M. 1971. *Instrumental Methods for the Analysis of Soils and Plant Tissue*. Soil Science Society of America, Inc., Madison, Wis.

Watson, M.E. and R.A. Isaac. 1990. Analytical Instruments for Soil and Plant Analysis. p. 691-740. In R.L. Westerman (ed.) *Soil Testing and Plant Analysis. 3rd ed.* Soil Science Society of America Book Ser. 3. SSSA, Inc., Madison, Wis.

Websites for Regional Soil Testing Procedures and Other Related Procedures:

Brown, J.R. (ed.). 1998. Recommended Chemical Soil Test Procedures for the North Central Region. North Central Regional Research Publication Bull. No. 221 (revised). Missouri Agricultural Experiment Station SB 1001, University of Missouri, Columbia, Mo. Available at http://muextension.missouri.edu/xplor/specialb/sb1001.htm (verified 1 Nov. 2005).

Burt, R. (ed.). 2004. Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42 Version 4.0. USDA-NRCS, Lincoln, Nebr. Available at http://soils.usda.gov/technical/lmm/ (verified 1 Nov. 2005).

Donohue S.J. (ed.). 1992. Reference Soil and Media Diagnostic Procedures for the Southern Region of the United States [Online]. Southern Coop. Ser. Bull. No. 374. Virginia Agricultural Experiment Station, Virginia Tech, Blacksburg, Va. Available at http://www.clemson.edu/agsrvlb/sera6/bulletinNo.374.pdf (verified 1 Nov. 2005).

Hanlon E.A. (ed.). 2001. Procedures Used by State Soil Testing Laboratories in the Southern Region of the United States [Online]. Southern Coop. Ser. Bull. #190-C. Southwest Florida Research and Education Center, UF-IFAS, Immokalee, Fla. Available at http://bioengr.ag.utk.edu/soiltestlab/pubs/SR_bulletin190.pdf (verified 1 Nov. 2005).

Richards, L.A. (ed.). 1954. Diagnosis and Improvement of Saline and Alkali Soils. Agriculture Handbook No. 60. USDA-ARS. Available at http://www.ars.usda.gov/Services/docs.htm?docid=10158 (posted 18 Oct 2005).

Sims, J.T., and A.M. Wolf (ed.). 1995. Recommended Soil Testing Procedures for the Northeastern United States. Northeastern Regional Pub. No. 493 (2nd edition). Agricultural Experiment Station Univ. of Delaware, Newark, DE. Available at http://ag.udel.edu/extension/agnr/soiltesting.htm (verified 1 Nov. 2005).

Reviewed by Steve Heckendorn, Laboratory Manager, Crop and Soil Environmental Sciences

---

Issued in furtherance of Cooperative Extension work, Virginia Polytechnic Institute and State University, Virginia State University, and the U.S. Department of Agriculture cooperating. Alan L. Grant, Dean, College of Agriculture and Life Sciences, and Interim Director, Virginia Cooperative Extension, Virginia Tech, Blacksburg; Wondi Mersie, Interim Administrator,1890 Extension Program, Virginia State, Petersburg.

May 1, 2009

Appendix F: Composted Leaf Litter Analyses

C/N Ratio Results

Steve Nagle <snagle@vt.edu> Tue, Oct 12, 2010 at 1:47 PM
To: Rachel Layman <rachelayman@gmail.com>

here you go.

			wt	%N	%C
9	Hort RLman Com A	9/8/2010	302.5	0.832427	14.97366
10	Hort RLman Com B	9/8/2010	295.1	0.772678	14.52646
11	Hort RLman Com C	9/8/2010	304.1	0.789298	15.57956

Steve

Steven M. Nagle Research Specialist Senior
Dept of Crop and Soil Environmental Sciences
Virginia Tech
313 Latham Hall Blacksburg, VA 24061
540-231-4521

Report Number
08-016-0254 **Page:** 1 of 2

Account Number
03198

Send To : Ms. Rachel Layman
Ms. Rachel Layman
301 Chowning Place
Blacksburg, VA 24060

Project : Compost Analysis

A&L Analytical Laboratories, Inc.
2790 Whitten Rd Memphis, TN 38133 • Phone (901) 213-2400 • Fax (901) 213-2440
The One Source.

Purchase Order :
Report Date : 1/25/2008
Date Received : 1/16/2008
Date Sampled :

REPORT OF ANALYSIS

Lab Number : 56733
Sample Id : 1

Analysis	Result	Quantitation Limit	Method	Date and Time Test Started	Analyst
Total Kjeldahl Nitrogen , %	0.68	0.02	RMMA 3.1	01/24/2008 12:15	DP
Moisture (Oven 105C) , %	51.1	0	AOAC 2.2.01	01/21/2008 09:11	LF
Total Boron , mg/Kg	17.2	2.27	SW-6010B	01/21/2008 08:34	JTR
Soluble Salts , mmhos/cm	0.52	0.01	SOLUBLE SALTS 1:2	01/21/2008 08:32	LF
pH , s.u.	7.3		SW-9045D	01/21/2008 09:25	LF
Total Aluminum , mg/Kg	4390	4.55	SW-6010B	01/21/2008 08:34	JTR
Total Calcium , mg/Kg	15200	22.7	SW-6010B	01/21/2008 08:34	JTR
Total Copper , mg/Kg	13.6	0.227	SW-6010B	01/21/2008 08:34	JTR
Total Iron , mg/Kg	7230	22.7	SW-6010B	01/21/2008 08:34	JTR
Total Magnesium , mg/Kg	4730	22.7	SW-6010B	01/21/2008 08:34	JTR
Total Manganese , mg/Kg	442	0.455	SW-6010B	01/21/2008 08:34	JTR
Total Phosphorus , mg/Kg	679	4.55	SW-6010B	01/21/2008 08:34	JTR

M. Scott McKee, Technical Director

Sample results are reported 'as received' and are not moisture corrected unless noted

Report Number
08-016-0254 **Page:** 2 of 2

Account Number
03198

Send To : Ms. Rachel Layman
Ms. Rachel Layman
301 Chowning Place
Blacksburg, VA 24060

A&L Analytical Laboratories, Inc.
2790 Whitten Rd Memphis, TN 38133 • Phone (901) 213-2400 • Fax (901) 213-2440

Project : Compost Analysis

Purchase Order :
Report Date : 1/25/2008
Date Received : 1/16/2008

REPORT OF ANALYSIS

Date Sampled :

Lab Number : 56733
Sample Id : 1

Analysis	Result	Quantitation Limit	Method	Date and Time Test Started	Analyst
Total Potassium , mg/Kg	1720	22.7	SW-6010B	01/21/2008 08:34	JTR
Total Sulfur , mg/Kg	783	4.55	SW-6010B	01/21/2008 08:34	JTR
Total Zinc , mg/Kg	28.6	0.455	SW-6010B	01/21/2008 08:34	JTR

Method Reference:
Official Methods of Analysis of AOAC International, 17th Edition, 1998
Recommended Chemical Soil Test Procedures for the North Central Region. NCR Research Pub. No. 221 Revised.
Recommended Methods of Manure Analysis, Peters et al, 2002, In Press
USEPA, SW-846, Test Methods for Evaluating Solid Wastes, Physical/Chemical Methods, 3rd Ed. Current Revision
Comments:

M. Scott McKee, Technical Director

Sample results are reported 'as received' and are not moisture corrected unless noted

VIRGINIA COOPERATIVE EXTENSION
SOIL TESTING LABORATORY

Person: GROOVER VELVA
Submitting: HORTICULTURE
Sample: Rachel Compost

911
Unit: VPI & SU CAMPUS

LABORATORY RESULTS

Sample ID	Lab ID	pH	Buf	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B	Sum Cat CEC	Acidity	Base Sat.	Ca Sat	Mg Sat	K Sat	OM	CCE
				---- lbs/A ----				---- ppm in soil (mg/kg) ----					---- meq/100g ----		---- % ----					
CPSTA	35433	7.40	N/A	71	575	3105	466	5.6	66.8	0.2	71.7	3.8	20.3	N/A	100.0	76.3	19.2	4.7	32.2	127.0
CPSTB	35434	7.63	N/A	65	371	2901	446	3.2	61.4	0.2	11.2	3.8	19.1	N/A	100.0	76.7	19.3	5.0	31.6	614.0

Appendix G: Seasonal Photographs of SRES Trees

Appendix H: Minirhizotron Setup

Minirhizotron camera inserted from top captures images of roots growing against the clear, 91.5 cm long tube.

Cap keeps out light and rain

91.5 cm

45°

Not to scale; adopted from Dr. Susan Day and Sara Guerkin.