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Impacts of Root Invigoration and its Individual Components on the Performance of red maple (*Acer rubrum*)

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IMPACTS OF ROOT INVIGORATION^{TM} AND ITS INDIVIDUAL COMPONENTS ON THE PERFORMANCE OF RED MAPLE (*ACER RUBRUM*)

A Dissertation
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Plant and Environmental Sciences

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by
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ABSTRACT

The Root Invigoration™ process involves soil decompaction with an air tool, amendment with organic matter and prescription fertilizer, and mulching. In the current study, we measured soil chemical and physical properties, tree characteristics, and root system responses to this process and its individual components. Treatments included Root Invigoration™ (AFM), mulch only (M), fertilization only (F), Airspade® tillage only (A), and an untreated control (C). The experiment was conducted from 2005-2007 at four urban sites: Anderson, SC; Boston, MA; Myrtle Beach, SC and Pittsburgh, PA. Soil strength was initially reduced by Airspade®, mulch and AFM; however only AFM-treated soils sustained this reduction over two seasons. Across all locations, soil organic matter content was increased with AFM and mulching.

The levels of six soil nutrients were increased by Root Invigoration™, while one nutrient was increased by an individual treatment. Tree condition ratings were significantly higher in AFM trees than control trees by the end of 2007. In two locations, increases in dbh were also greater for AFM trees. At the end of 2006, estimated chlorophyll concentrations were higher in AFM trees than in the A or M treatments. Foliage of AFM trees had higher levels of phosphorus and potassium than foliage of fertilized trees. Mulched soils (both AFM and M) frequently had higher soil moisture content. During a drought period in 2007, pre-dawn leaf water potential was higher for M trees on two dates and for AFM trees on one. Although there were differences in root length density (cm root/cm^3 soil) among treatments in 2006, there were none in 2007. Mean root diameter was increased with fertilization. Root lifespan was reduced with M and AFM treatments. Time until root browning was also reduced with A, M and AFM, however AFM merely reflected the influence of the individual treatments. M and AFM shifted a greater proportion of fine roots to the upper 33.3 cm of the soil profile.

DEDICATION

I would like to dedicate this work to Jaime and Crosby. Thank you for giving me the inspiration to keep going when I felt like I couldn’t. It’s been quite a ride!

I would like to offer my thanks to my advisor, Dr. Christina Wells, for constantly challenging me to do my best.

I also owe this opportunity to Robert Bartlett Jr. Without his willingness to take a chance on me, I would not have had this privilege.

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CHAPTER I

LITERATURE REVIEW

Challenges of Urban Soils

Many tree species have the potential to live over 100 years, but the average life span of an urban street tree is estimated at only ten years (Foster and Blaine, 1978). Clearly, the urban environment is stressful to trees, and research suggests that much of this stress is caused by soil factors (Watson et al., 1996). Homeowners, municipalities and tree care companies would all benefit from successful strategies for improving root growth conditions in urban soils. Unfortunately, few effective treatment options exist.

Urban soils are a challenging medium for tree growth. They have frequently been disturbed through the processes of mixing, filling and contamination (Craul, 1985), and they tend to be highly compacted, with bulk densities higher than those of nearby forest soils (Close et al., 1996a). This compaction is often the result of human activity and the infrastructure that is developed to support these activities (Craul, 1985). Compacted soils hinder tree development by physically restricting root growth, reducing gas exchange and limiting soil water availability (Craul, 1992).

While forest soils have a well-developed humus layer, urban soils typically lack an upper organic horizon (Fraedrich and Ham, 1982). Organic matter in soils helps to maintain proper structure, air and water movement and retain nutrients. However, in urban settings, plant debris is often removed and these soils have very low levels of organic matter. The removal of this debris also disrupts the cycling of mineral nutrients back into the soil. As a result, urban soils are often deficient in many minerals and may require fertilization to ensure the health and growth of trees planted in these conditions (Struve, 2002).

Urban sites also tend to have lower levels of soil moisture than nearby forested areas. Soil compaction, higher temperatures, lower relative humidity, limited soil volumes, impervious surfaces, low organic matter content and turf competition all contribute to reduced water availability at urban sites (Close et al., 1996a; Rhoades and Stipes, 1999). Furthermore, pavement, buildings, and automobiles reradiate large amounts of heat, which increases evapotranspiration and quickly dries the soil.

Trees growing under water-limited conditions close their stomates in an effort to restrict water loss (Close et al., 1996b). Because this strategy also limits photosynthesis, both tree growth and the accumulation of carbon reserves are reduced. When drought stress becomes chronic, the tree's ability to defend itself against diseases and pests is reduced and its lifespan is shortened (Harris et al., 2004).

Soil water deficiency is sensed first by the tree's fine root system. These small, absorbing roots (< 1 mm in diameter) are distributed shallowly in the soil profile. It is estimated that 80% of fine roots are found in the upper 30 cm of the soil (Craul, 1992), and fine root distribution may be even shallower when a protective layer of mulch or organic matter is present (Harris et al., 1999). Tree roots spread widely from the trunk base, extending from 2 to 4 times the diameter of the canopy dripline when growth is unrestricted (Gilman et al., 1987; Harris et al., 1999; Perry, 1982). Therefore, it is this wide, shallow soil zone on which soil remediation efforts should be concentrated in urban settings.

The upper soil levels are subjected to many processes that increase the soil's resistance to root penetration. Because this limits root system development in urban soils, arboricultural techniques that reduce soil impedance merit further exploration (Day and Bassuk, 1994). Unfortunately, urban trees can be subjected to additional root system damage from traditional soil decompaction methods such as mechanical tillage (Watson et al., 1996). It is challenging to improve the physical properties of the soil within the root zone without causing significant root damage in the process.

Root Invigoration™

A new process has recently been developed to promote the performance of urban trees while reducing additional stress to the root system. The Root Invigoration™ (AFM) process, developed by the F. A. Bartlett Tree Expert Co., is designed to promote fine root function by incorporating organic matter and fertilizer in the rooting zone while simultaneously reducing soil compaction and aerating the soil.

In the basic AFM program, the soil is treated in a circular area with a radius of 3-5 times the tree's dbh (diameter at 4.5 feet above soil level), with a minimum radius of 1.5 m. Turf is removed or killed in this area prior to treatment. Soil is then loosened to a depth of 15-20 cm (6-8 in.) using an Air Spade® (Concept Engineering Group, Verona, PA), a tool that channels compressed air through a specialized tip.

Next, the treated area is amended with composted organic matter and fertilizer products based on prior soil analyses. These amendments are homogenized into the existing soil with the Air Spade® to create a soil environment that may be more conducive to root growth. Finally, the treated area is mulched to a depth of 5-7.5 cm (2-3 in.) to help retain soil moisture. Irrigation is applied following treatment to settle the soil and counteract the drying effects of the Air Spade® tillage.

Preliminary observations have shown changes in fine root growth of AFM-treated trees. This is often followed by a denser, greener canopy the following season, although no experimental evidence exists to support such anecdotal observations. The current research project aims to quantify the response of red maples in four locations to the Root Invigoration process. Additional treatments include control, Air Spade® tillage only, mulching only and fertilization only. Data will be analyzed to determine if any of these processes significantly improve tree growth and performance.

The following pages review key topics in tree biology that form the foundation of this research project. Findings from previous research are summarized and used to lay the groundwork for our experimental design.

Tree Mineral Nutrition

Plants require 13 specific mineral elements in order to grow normally (Table 1.1). When supplied with essential elements, water, CO_2, O_2, and sunlight, plants can manufacture all the compounds they need for growth (Taiz and Zeiger, 2002). Roots obtain these mineral nutrients from the soil in ionic form; they are then transported throughout the plant in the xylem and used in biological processes (Taiz and Zeiger, 2002). Without proper nutrient levels, critical metabolic processes will be disrupted.

Urban shade trees are fertilized to replace nutrients that have been depleted or are unavailable for uptake. Soil testing, foliar nutrient analysis and management goals are the basis of prescription fertilization programs in the tree care industry (Struve, 2002).

Nitrogen, in particular, is frequently applied, as it affects growth rate of established shade trees more than P or K and is often the only nutrient that increases growth under field conditions (Neely and Himelick, 1966; Philipson and Coutts, 1977; van de Werken, 1984; Watson, 1994).

Nitrogen is applied to the soil to stimulate growth (Gilman et al., 2000), although it generally stimulates shoot growth to a greater extent than root growth (Philipson and Coutts, 1977). Established landscape trees have shown mixed responses to nitrogen applications. Warren (1993) reported that leaf area and top dry weight of flowering dogwood (*Cornus florida*) increased quadratically with increasing nitrogen. However,

Table 1.1. Major nutrients, roles within the plant and deficiency symptoms[1].

Nutrient	**Role**	**Key deficiency symptoms**
Nitrogen	Structural component of proteins, enzymes, DNA and RNA, chlorophyll, NADH, NADPH, choline and indoleacetic acid.	Small leaves; chlorosis and abscission of older leaves. Premature defoliation beginning in older foliage. Root growth reduced and branching restricted, but increased root/shoot ratio.
Phosphorous	Buffers cell pH and maintains homeostasis. Regulates enzyme activity. Energy release through P-P bond breakage and NADP+ reduction to NADPH. Constituent of nucleic acids (DNA, tRNA, mRNA and rRNA). Present in membrane phophoslipids and as a lipid anchor constituent of some lipo-proteins and lipo-polysaccharides.	Darkish green-purple color of older leaves. Sparse slightly small, distorted foliage. Shoots normal length, but small diameter. Early leaf drop.

Table 1.1. Major nutrients, roles within the plant and deficiency symptoms[1] (continued).

Nutrient	**Role**	**Key deficiency symptoms**
Potassium	Maintains plant water status and cell turgor pressure. Controls opening and closing of stomata. Translocation of newly synthesized carbohydrates. Involved in cellulose synthesis.	Marginal and interveinal chlorosis, followed by scorching in older leaves first. Shoot tips die back late in season. Few flowers. Growth slows because sugars and starches accumulate where formed. Cell walls and stems weak and plants lodge, stems break.
Calcium	Cell elongation in the shoot and growing tip of the roots. Binds cell walls together by binding free carboxyl groups of pectin in the middle lamella between adjacent cell walls.	Reduction in meristimatic tissue growth in growing tips and young leaves. Leaves deformed and chlorotic, then necrotic margins.
Sulfur	Di-sulfide bonds are formed and are involved in protein structure. Involved in conformation and activity of many enzymes. Constituent in many enzymes, vitamins and hormones.	Leaves pale yellow-green both young and old. Stunted growth. Short thin and woody stems.
Iron	Related to changes in oxidation-reduction states and electron transfer reactions. Part of protein ferredoxin. Required for nitrate reduction, suphate reduction, N_2 assimilation and energy production (NADP).	Young leaves display interveinal chlorosis. Exposed leaves bleach and scorch. Small leaves. Shoot normal length, but small diameter. Twig dieback and defoliation if severe.

Table 1.1. Major nutrients, roles within the plant and deficiency symptoms[1] (continued).

Nutrient	Role	Key deficiency symptoms
Manganese	Involved in oxidation-reduction process. Cofactor for numerous enzymes. Element of the enzyme superoxide dismutase, neutralizes the free radicles formed by the splitting of water during the Hill reaction of photosynthesis. Involved in pollen germination and pollen tube growth.	Chlorosis between veins of older leaves developing into necrotic interveinal spots. Leaf may be limp. Shoot growth reduced.

[1](Harris et al., 1999; Mills and J. Benton Jones, 1996)

applications of nitrogen greater than 14 to 24 g N/m^2 (3 to 5 lb N/1000 ft^2) per year have rarely shown any benefit (Gilman et al., 2000). Applications rates higher than 29g N/m^2 (6 lb N/1000ft^2) annually are generally not recommended (Smiley et al., 2002).

The type of fertilizer and the application method can also influence tree response. In some cases, slow-release fertilizers have been shown to provide a greater growth benefit than ammonium nitrate and urea fertilizers, but other studies have found that all fertilizer types provide similar benefits (Gilman et al., 2000).

Application methods may be more important than the type of nitrogen supplied, although again the differences appear to be small (Struve, 2002). Subsurface applications do not appear to provide a greater growth benefit than broadcast surface applications (Gilman et al., 2000; Neely, 1980). In fact, Van de Werken (1984) reported that broadcast applications promote more growth than applications of identical products in 46 cm (18 in) deep holes, although the depth of these holes may have placed the fertilizer below the region of optimum root uptake.

Fertilizer applications may alter root system growth and behavior because roots tend to proliferate in areas of soil that have favorable chemical and physical properties (Eissenstat and Caldwell, 1988). Lateral root growth increases in nutrient-rich areas of soil (Watson, 1994). Root density can be 10-15 times greater in nutrient-rich patches than in unfertilized areas, and the relative growth rate of roots may be increased 3-6 times in fertilized zones (Eissenstat and Caldwell, 1988).

While nitrogen fertilization may increase root density in the fertilized zone, it can also reduce overall fine root growth if excessive (May et al., 1965; Watson, 1994). When fertilizers are applied to the soil, root proliferation is primarily located near the application site, while root growth elsewhere in the system remains relatively unchanged or may decrease (Eissenstat and Caldwell, 1988; Philipson and Coutts, 1977).

When the root system of Lodegepole pine (*Pinus contorta*) was split into high and low nutrient regimes, roots in the low nutrient regime had only half the dry weight of those in the high nutrient regime (Coutts and Philipson, 1977). When only one side of the root system of Sitka spruce (*Picea sitchensis*) received favorable treatment, that side often grew more than either side of the tree that received uniform favorable treatment. (Philipson and Coutts, 1977)

The regenerative ability of the root system is demonstrated by its ability to recover from low nutrient conditions when adequate nutrients become available again (Coutts and Philipson, 1977). Sitka spruce roots in low nutrient regimes grew slowly or not at all and turned brown. When these roots were moved into high nutrient regimes, they responded with increased growth and vigor (Coutts and Philipson, 1977).

The previous findings suggest that proper fertilization of low-nutrient urban soils may result in significant increases in fine root growth and tree performance. In the current project, we will evaluate the effects of fertilization alone and as a component of the Root Invigoration process. We expect both fertilized and Root Invigoration-treated trees to have increased fine root density in the treated soil and increased above-ground growth.

Soil Compaction

The primary function of the fine root system is to acquire water and nutrients from the soil. In the forest environment, soil physical and chemical properties are conducive to root growth. But soils in the urban environment are much different than their forest counterparts and can limit root growth (Alberty et al., 1984; Patterson, 1977). One of the most common and detrimental problems in urban soils is compaction (Craul, 1992).

Urban soils become compacted by vehicles, construction disturbance, foot traffic and lack of cover (Craul, 1985; Pan and Bassuk, 1985). Compaction decreases total pore space, reduces the proportion of large pores, and increases bulk density and mechanical resistance (Conlin and Driessche, 1996; Craul, 1985). Bulk density is a measure of soil compaction and is calculated by dividing a soil sample's dry mass by its volume (expressed in g/cc) (Black, 1964). Soil strength, a related property, refers to the ability of a soil to resist an applied force (Taylor, 1971). High levels of strength decrease the ability of plant roots to grow through the soil.

Soil compaction in urban settings is usually the result of human activity and not natural processes (Craul, 1985). Urban areas have infrastructure and hardscape features that require extensive traffic and equipment usage during development. Moreover, many buildings and features must be built upon soil that has undergone a specified amount of compaction. Furthermore, measures that are taken to protect soil from being compacted during construction activities are rarely effective (Randrup and Dralle, 1997). This soil then becomes the medium for tree root growth and the extraction of water and nutrients.

Typical soil bulk densities in urban environments are often inhospitable to root growth. Bulk densities of 1.25 to 1.6 g/cc are generally considered restrictive to root growth, depending on soil type and moisture content, while building brick bulk densities range from 1.4 to 2.3 g/cc (Gilman et al., 1987). Soils beneath shade trees in Washington, D. C. had bulk densities of 1.7 to 2.2 g/cc (Patterson, 1977), and these readings are not atypical for urban areas. Soils within construction zones in the Minneapolis/St. Paul metropolitan area were shown to have a mean bulk density of 1.56 g/cc, which was significantly higher than nearby undisturbed soil (Alberty et al., 1984). The mean bulk density of 50 roadside tree planting pits in urban Hong Kong was 1.66 g/cc, while soils of highway median plantings in Charlotte, NC, had a mean bulk density of 1.75 g/cc (Jim, 1998; Smiley et al., 1990).

Numerous examples of poor tree performance on compacted soil have been documented. Growth of *Forsythia ovata* and *Cornus sericea* was significantly reduced in response to increasing soil bulk density (Alberty et al., 1984). Helms and Hipkin showed dramatic decreases in growth of ponderosa pine (*Pinus ponderosa*) with increasing bulk density (1986). Increased levels of soil compaction were associated with shorter needles, lower root dry weights, lower net photosynthesis, higher respiration and lower concentrations of mineral nutrients in *Pinus contorta* (Conlin and Driessche, 1996). *Ailanthus altissima* root distribution was shifted from having few surface lateral roots in uncompacted soil, to more numerous shallow roots that elongated longer distances in compacted soil (Pan and Bassuk, 1985). Total root dry weight was also reduced due to compaction.

Reduced root growth and impaired physiological function underlie the poor performance of trees on compacted soils. In addition to the direct effect of compaction on root growth, there are many indirect effects of soil compaction on soil gas exchange, soil water availability, and soil chemistry (Craul, 1992).

High soil strength and small pore size limit root growth in compacted soils (Alberty et al., 1984). With increasing soil resistance, roots become less able to proliferate and branch (Glinski and Lipiec, 1990). This inhibition creates roots that are larger in diameter and often shortened (Glinski and Lipiec, 1990). Day and Bassuk (1994) reported that root systems of trees on compacted soils tend to be more branched and thickened. This occurs because cell extension is reduced, yet cell numbers are unchanged (Glinski and Lipiec, 1990). Root branching may also be reduced in soils with high mechanical resistance. These affects can result in a decrease in the uptake of nutrients, particularly phosphorus (Glinski and Lipiec, 1990).

Compacted soils not only present physical challenges to root systems, but also impact root physiological processes. Compaction reduces oxygen exchange between the roots and the atmosphere because gas diffusion occurs mainly through large macropores that are destroyed when the soil is compacted (Gilman et al., 1987; Horn et al., 1995; Kozlowski, 1999; Patterson, 1977). The soil environment then enters an oxygen-depleted or anaerobic state (Kozlowski, 1999; Percival and Keary, 2008). Water movement through compacted soils will also be slower, and this tightly-bound soil water will create an obstruction for gas diffusion through the soil (Craul, 1985). Under the resulting low-oxygen conditions, tree roots must rely on inefficient anaerobic fermentation for energy, a process which does not supply sufficient energy to preserve root health over the long term (Kozlowski, 1999). Lack of cellular energy can lead to the breakdown of transmembrane electrochemical gradients and result in leakage of ions back into the soil (Kozlowski, 1999).

Populations of beneficial aerobic microbes decline in low-oxygen soils, while those of potentially-harmful anaerobic bacteria increase (Taiz and Zeiger, 2002). Anaerobic microbes reduce ions such as Fe^{3+} and SO_4^{2-} into more toxic forms and can produce additional bacterial metabolites that are damaging at high concentrations (Taiz and Zeiger, 2002).

Root physiological process can also be impacted by changes in the water availability in compacted soils. Compacted soils have an increased proportion of micropores to macropores. As these soils dry, water recedes into the micropores, where it assumes a very small radius of curvature and large negative water potential (Taiz and

Zeiger, 2002). This drastically lowers the water potential of the soil and makes root water uptake more difficult (Taiz and Zeiger, 2002).

When water is introduced to water-deficient compacted soils, they are susceptible to crusting or reduced water permeability (Craul, 1985; Horn et al., 1995), again leading to water stress in the tree. Because root growth is often restricted in compacted soil, the soil volume from which the tree can extract water may also be reduced (Day and Bassuk, 1994).

Improving Soil Physical Properties

Because soil compaction is profoundly detrimental to root growth and function, many techniques have been proposed for alleviating it. Most have met with only limited success. Pittenger and Stamen (1990) found that several traditional compaction mediation techniques provided no benefit to landscape trees. Methods evaluated included power auger holes to a depth of 45 cm, power auger holes backfilled with sand and bark, high-pressure water jet-prepared holes, and holes lined with perforated plastic pipe and backfilled with gravel. These and similar aeration methods have been used for years with limited results. The authors suggest that in sandy loam soils, soil moisture may influence tree performance more than soil aeration (Pittenger and Stamen, 1990).

Vertical mulching, which is usually conducted by drilling vertical channels throughout the root zone and backfilling with porous amendments, has been used for some time as a treatment option for compacted soils under established landscape trees. However, when perlite was used as a backfill, vertical mulching had no effect on tree health (Kalisz et al., 1994).

Radial trenches originating near the trunk and extending outward towards the drip line were shown to be beneficial when filled with friable soil (Day and Bassuk, 1994). Proper mulching increased the vigor of landscape trees, but Fraedrich and Ham (1982) noted that natural incorporation of organic matter into the soil profile from mulch is a slow process.

A variety of pneumatic decompaction devices have been developed to physically break up compacted soils beneath landscape trees. Such equipment is designed to fracture compacted soil layers by introducing pressurized air or nitrogen (Smiley et al., 1990). The resulting fractures are often filled by fertilizer, amendments and/or water.

In a test of several decompaction machines, none reduced bulk density near the soil surface, and increased aeration was only seen along the soil fracture plane (Smiley et al., 1990). In a separate test, the Terralift soil aerator improved bulk density, porosity, saturated hydraulic conductivity and air permeability in a sandy loam but not a loam soil (Rolf, 1992). When testing was conducted using an advanced version of a pneumatic decompaction machine, the Terravent™, Smiley found no reduction in bulk density and concluded that any soil fracturing effect was likely temporary (2001). A recent study concluded that this same device had no effect on fine root length, mass or diameter in moderately compacted clay loam soil (Hascher and Wells, 2007).

Root Invigoration™ uses the Air Spade® to treat a larger portion of root zone than previously-mentioned methods. The Air Spade® is used to channel high-pressure air into the soil, loosening and tilling it in a manner akin to traditional mechanical tillage, but without causing significant damage to the root system. The use of this process may provide a larger area for root proliferation, leading to increased water and nutrient uptake from the soil. Improved fine root density, soil bulk density, and above-ground growth are expected in trees receiving Air Spade® decompaction alone and as a component of the Root Invigoration™ process.

Organic Matter

Native forest soils not only have relatively uncompacted soil, but also years of organic matter buildup incorporated into the upper soil horizons. Root Invigoration™ is an attempt to recreate this type of soil in the urban environment, and organic matter addition is therefore a fundamental component of the Root Invigoration process.

Organic matter is the soil fraction composed of once-living material, including plant and animal remains and the cells and tissues of soil organisms (USDA, 1996). Although organic matter only accounts for 2-5% of the volume of most soils, it is extremely important because it stores and supplies nutrients through high cation and anion exchange capacities. Organic matter also increases the ability of the soil to store air and water, makes the soil more stable and friable, and helps to maintain a lower bulk density (USDA, 1996).

In the urban landscape where aesthetics are a major concern, nutrient-rich organic matter such as leaf litter is often removed from the soil surface (Craul, 1985; Harris et al., 2004). This organic matter, if left to decompose, would have returned valuable resources to the soil. Soil-inhabiting organisms use organic matter as an energy source and populations of these organisms can be reduced by low levels of organic matter (Craul, 1985).

Organic matter incorporation into backfill during transplanting has often been a recommendation within the green industry. However, some organic amendments such as aged pine bark, Mr. Natural™ Concentrated Landscape Media (Mr. Natural, Dahlonega, GA), and Nature's Helper (Smith Trucking Company, Cumming, GA), did not increase root growth at transplant in red maple (Smalley and Wood, 1995). Although transplanted trees did not respond to organic matter amendment of the backfill, it is possible that established landscape trees might. The organic additions should benefit these established trees more because the roots of these trees often exist in compacted, nutrient-poor soils instead of the more favorable environment of the loosened backfill.

A study was conducted to measure the impact of soil replacement in the root zone of established white oaks (*Quercus alba*). One year after treatment, root density was increased 2.3 times in replacement soils that contained 50% hardwood leaf compost and 50% native soil (Watson et al., 1996). After four years, root density in 100% compost replacement soil was 3.2 times higher than that in control soil. After fourteen years, increases in root density remained limited to the trenches and had not changed in adjacent soils (Watson, 2002).

Rooting depth of *Tilia* spp. and *Platanus* x *acerifolia* was increased by replacing native soils with a custom mix of sand, composted organic matter and fertilizer using a process known as RADOSAN to hydraulically remove soil from root in holes or pits (Watson et al., 1996). Trees that were previously experiencing decline showed an increase in root and top growth after treatment. The principle of this process is very similar to that of Root Invigoration™.

One of the most common forms of organic matter in the landscape is mulch. Mulch suppresses weeds, conserves soil moisture, moderates soil temperatures, increases water infiltration, reduces compaction, and improves soil structure and nutrient status over time by increasing organic matter content (Greenly and Rakow, 1995; Watson et al., 1996). Even mineral mulches, such as lava rock and pea gravel, increased soil moisture and decreased soil temperature when compared to bare soil (Iles and Dosmann, 1999). Spring soil temperatures are highest on non-mulched trees, causing earlier bud break and leaf expansion than on organic mulched trees (Litzow and Pellett, 1983).

Many studies have shown improvements in tree health due to mulching. Proper mulch application significantly improved above ground growth of pin oak (*Quercus palustris*) and white pine (*Pinus strobus*) (Greenly and Rakow, 1995). In coarse and fine textured soils, red, sugar (*Acer saccharum*) and silver maples (*A. saccharinum*) had greater shoot growth when mulched (Fraedrich and Ham, 1982). In sandy soils, mulching also improved height and diameter of silver maples. This is likely due to the conservation of soil moisture, since sandy soils retain less moisture than clay soils (Fraedrich and Ham, 1982). The conservation of soil moisture by mulching also can reduce physical resistance of the soils (Fraedrich and Ham, 1982).

In the same study, root weights from samples near the outer mulched areas were significantly higher than outside the mulch (Fraedrich and Ham, 1982). Root densities for red maple were significantly higher in the mulch itself and upper mulched soil depths than in unmulched soil (Watson, 1988). Fine root density of white oak was also increased after turf removal and mulching (Himelick and Watson, 1990).

Organic matter amendment and mulching are components of Root Invigoration™. In the current project, we will quantify the benefits of mulching alone and as a component of the Root Invigoration™ process. We expect increases in fine root density and decreases in soil resistance with the addition of organic matter and mulch.

Assessing Root Response

We expect treatments to have a profound effect on soil and root properties, but accurately measuring root system responses can be challenging. Spatial heterogeneity in soil parameters is high, and site impacts from frequent sampling can be significant. We will, therefore, use minirhizotrons (root observation tubes) to more accurately evaluate root activity with minimal disturbance.

Minirhizotrons are plastic tubes installed in the ground which allow specially-designed camera systems to capture images of fine roots that have grown against their outer surface (Johnson et al., 2001). They allow researchers to view root activity with minimal disturbance and to accurately quantify root numbers, length and production (Johnson et al., 2001).

Minirhizotrons are particularly useful for observing root production, lifespan, and mortality, which cannot be determined from traditional sampling methods (Hendrick and Pregitzer, 1992). Fine root production, growth, and turnover can be determined if sampling frequency is short enough to provide accurate data (Hendrick and Pregitzer, 1992; Johnson et al., 2001). Root lifespan can also be estimated from minirhizotron images, although physical separation of live and dead roots based on staining or brittleness is not possible.

In the current study, we will install minirhizotrons at one site to provide more thorough insight into treatment effects on fine root production, growth and lifespan. Frequent minirhizotron imaging will allow for reliable assessment of root system dynamics. If the soil environment is favorable, the root system is expected to produce young, efficient roots to harvest water and mineral nutrients from the soil (Eissenstat and Yanai, 1997). As depletion zones develop around these active roots, they will turn over rapidly and be replaced by new roots in less depleted zones. Biweekly documentation of root dynamics will confirm or refute these hypotheses.

Experimental Overview

Our experiment will take place at four research sites: Anderson, SC; Myrtle Beach, SC; Boston, MA and Pittsburgh, PA. Five treatments (Root Invigoration™, Air Spade® tillage, Mulch, Fertilizer and control) will be applied to ten replicate trees at each site, for a total of 200 experimental units. Site pre-treatment data are presented in Tables 1.2, 1.3 and 1.4.

Minirhizotron images will be collected bi-weekly at the Anderson, SC, site throughout the growing season to assess root system dynamics in response to treatments. Pre-dawn water potential and chlorophyll fluorescence will also be measured bi-weekly basis the Anderson, SC, site. Phenology, soil temperature and soil water content will be continuously monitored. The full measurement schedule for all sites is given in Table 1.5.

Table 1.2. Chemical properties of pre-treatment soil collected from each research site. Within a row, means (+/- 1 standard error) depicted with different letters are significantly different using Fisher's LSD procedure ($\alpha = 0.05$).

Parameter	Anderson[1]	Boston[2]	Myrtle Beach	Pittsburgh
ENR[3] (kg/ha)	85.5 ± 14.6	114	54.7 ± 9.5	74.4 ± 2.4
Soil P (ppm)	12.3 ± 2.6^{c}	288^{a}	38.3 ± 3.0^{c}	115.3 ± 20.2^{b}
Soil K (ppm)	138.7 ± 14.4^{b}	87^{c}	43.5 ± 7.4^{d}	276.7 ± 5.2^{a}
Soil Mg (ppm)	112.7 ± 23^{b}	99^{b}	64.3 ± 8.7^{b}	452.7 ± 27.9^{a}
Soil Ca (ppm)	942.3 ± 274.3^{b}	977^{b}	3648.5 ± 967.8^{ab}	5133.3 ± 768.4^{a}
Soil Na (ppm)	13.6 ± 0.3^{c}	39^{b}	30.3 ± 7.0^{ab}	85.3 ± 3.3^{a}
Sol. Salt (ppm)	0.3 ± 0	0.3	0.3 ± 0	0.2 ± 0.03
Soil Fe (ppm)	51.7 ± 3.7^{c}	295^{b}	134.5 ± 24^{c}	478.7 ± 31.9^{a}
Soil Mn (ppm)	104.3 ± 39.8^{b}	24^{b}	7.8 ± 1.4^{b}	312 ± 21.2^{a}
Soil Cu (ppm)	1.6 ± 0.3^{c}	9.6^{a}	0.6 ± 0.1^{c}	4.0 ± 0.5^{b}
Soil Zn (ppm)	2.7 ± 1.2^{b}	14.4^{a}	2.5 ± 0.5^{b}	5.2 ± 0.5^{b}
Soil OM (%)	2.8 ± 0.9	4.6	1.6 ± 0.4	2.0 ± 0.1
Soil CEC (meq/100g)	7.7 ± 1.1	9.6	19.0 ± 5.0	17.2 ± 1.8
Soil pH	5.7 ± 0.4	5.5	7.9 ± 0.1	6.8 ± 0.07

[1] Chemical properties based on: Anderson n=3; Boston n=1; Myrtle Beach n=4; Pittsburgh n=3. Bulk density based on: n=50 at all sites.

[2] Post hoc analysis cannot be performed because *n*=1

[3] Estimated Nitrogen Release based on soil organic matter

Table 1.3. Pre-treatment properties of red maple at four locations. Within a row, means (+/- 1 standard error) depicted with different letters are significantly different using Fisher's LSD procedure ($\alpha = 0.05$).

Parameter	N	Anderson	Boston	Myrtle Beach	Pittsburgh[1]	overall *p*-value
Foliar N (%)	50	1.55 ± 0.03^{b}	1.84 ± 0.03^{a}	$1.49 \pm .04^{b}$		.000
Foliar P (%)	50	0.09 ± 0.00^{c}	0.31 ± 0.01^{a}	0.23 ± 0.01^{b}		.000
Foliar K (%)	50	0.63 ± 0.03^{c}	0.92 ± 0.03^{a}	$0.74 \pm .03^{b}$		.000
Foliar Ca (%)	50	0.75 ± 0.02^{b}	0.72 ± 0.02^{b}	$1.61 \pm .07^{a}$		.000
Foliar Mg (%)	50	0.18 ± 0.01^{b}	0.24 ± 0.01^{a}	$0.26 \pm .01^{a}$		.000
Foliar Zn (ppm)	50	24.34 ± 0.93^{b}	28.74 ± 0.75^{b}	42.5 ± 2.68^{a}		.000
Foliar Cu (ppm)	50	8.98 ± 0.95	9.52 ± 0.30	9.36 ± 0.69		.856
Foliar Mn (ppm)	50	329.3 ± 30.27^{a}	143.76 ± 8.59^{b}	97.6 ± 16.04^{b}		.000
Foliar Fe (ppm)	50	106.12 ± 3.97^{c}	131.74 ± 4.33^{b}	159.2 ± 7.83^{a}		.000
Foliar S (%)	50	0.12 ± 0.00^{c}	0.13 ± 0.00^{b}	0.14 ± 0.00^{a}		.000
Foliar Na (ppm)	50	20.32 ± 0.57^{b}	29.22 ± 1.59^{b}	217.1 ± 28.7^{a}		.000

Table 1.3. Pre-treatment properties of red maple at four locations. Within a row, means (+/- 1 standard error) depicted with different letters are significantly different using Fisher's LSD procedure ($\alpha = 0.05$) (continued).

Parameter	N	Anderson	Boston	Myrtle Beach	Pittsburgh[1]	overall *p*-value
SPAD[2]	50	37.1 ± 0.38^{a}	37.9 ± 0.37^{a}	29.4 ± 0.92^{b}		000
DBH (cm)[3]	50	11.8 ± 0.36^{b}	12.7 ± 0.20^{b}	6.17 ± 0.25^{c}	15.9 ± 0.99^{a}	.000
Condition[4]	50	7.04 ± 0.21^{a}	4.08 ± 0.07^{c}	4.94 ± 0.27^{b}		.000

[1] Foliage was not present at time of treatment application

[2] Mean foliar chlorophyll content measured with Minolta SPAD-502 (Minolta Inc, Japan)

[3] Stem diameter in inches measured with a diameter tape at approximately 4.5 feet from ground height

[4] Visual analysis based on a 1-10 scale assessing foliage color, crown density, dieback and vigor

Table 1.4. Physical properties of pre-treatment soil collected from each research site. Within a row, means (+/- 1 standard error) depicted with different letters are significantly different using Fisher's LSD procedure ($\alpha = 0.05$).

Parameter	N	Anderson	Boston	Myrtle Beach	Pittsburgh[1]	overall *p*-value
RLD[1]	50	6.94 ± 0.57b	10.87 ± 0.63a	3.14 ± 0.29c	6.64 ± 0.60b	.000
RMD[2]	50	0.005 ± 0.0005a	0.002 ± 0.0001c	0.0033 ± 0.0005bc	.0036 ± .0004ab	.003
Root diameter	50	0.66 ± 0.17a	0.64 ± 0.01a	0.63 ± 0.13a	0.49 ± 0.02b	.000
Bulk Density	50	1.41 ± 0.02b	1.14 ± 0.04d	1.74 ± 0.04a	1.25 ± 0.03c	.000

[1] Root length density (cm/cc)

[2] Root mass density (g/cc)

Table 1.5. Site measurement schedule.

Measurement	# per tree	Boston	Pittsburgh	Myrtle Beach	Anderson
DBH	1	F[1]	F	F	F
Internode Elongation	3	F	F	F	F
Foliar nutrients	1	S,F	S,F	S,F	S,F
SPAD					
Soil nutrients	2	S	S	S	S
RLD and mycorrhizae	2	S,F	S,F	S,F	S,F
Visual rating	1	S,F	S,F	S,F	S,F
Bulk Density/Soil Strength	1	S	S	S	S
Minirhizotron sampling	1				bi-weekly
Pre-dawn water potential	3				bi-weekly
Chlorophyll fluorescence	3				bi-weekly
Soil temperature					continuous
Soil water content					continuous
Phenology notes					bi-weekly

[1] F=Fall, S=Spring

This study will provide insight into the response of red maple to the Root Invigoration™ process and its individual components. The results may encourage the arboriculture industry to promote complex soil remediation programs, or, alternately, it may suggest that less invasive and more affordable treatments provide adequate results.

CHAPTER II

MATERIALS AND METHODS

Boston, MA

Site characterization and background data

The experiment was performed in a common area surrounding the library of Stonehill College in Easton, Massachusetts. The site had been a parking lot and was subsequently developed as green space after the construction of the library. As a result, the soils at the site were disturbed and shallow with a significant gravel component. The site was planted with red maple (*Acer rubrum*) approximately six years ago, and the trees had not received fertilizer or pesticide applications since that time.

In August 2005, fifty red maples surrounding the library and were visually rated by trained arborists on a scale of 0-10, with 0 indicating that the tree was dead and 10 indicating that it possessed a dense, dark green and vigorous canopy. Location data for each tree were collected using a Trimble ProXR GPS receiver with the TSC1 data collector (Trimble Navigation Limited, Sunnyvale, CA).

In August 2005, stem diameters at 1.4 meters (4.5 ft.) above ground level (dbh) were measured. Mean foliar chlorophyll content was estimated by averaging SPAD meter readings from three randomly-selected leaves per tree (Minolta SPAD-502, Minolta Inc, Japan). Foliar nutrient content was assessed by collecting approximately 100 g (3.5 oz.) of mature leaves from each tree and submitting these samples to the Clemson University Agricultural Services Laboratory for analysis (http://www.clemson.edu/agsrvlb/).

Soil bulk density and root length density were assessed by collecting two soil cores from beneath each tree approximately 0.75 m (2.5 ft.) from the trunk. The cores collected for bulk density were trimmed to 7.6 cm (3 in.); those for root density were trimmed to 15.2 cm (6 in.). Turf, leaf litter and organic matter layers were removed from the top the cores. Both were stored in wax-lined paper bags to prevent moisture loss. Soil samples were stored at 5°C (41°F) for less than one week before processing.

Bulk density samples were transferred to aluminum trays and dried for seven days at 65°C (149°F) to remove all moisture. Samples were then weighed to calculate the bulk density (g/cc) of the soil.

Root length density samples were washed through a 1 mm sieve to remove soil and retain fine roots. Root samples were further screened by hand to remove additional soil and organic matter and were stored in 50% ethanol at 5°C prior to length measurement. The total root length of each root sample was measured with the WinRhizo system (Regent Systems, Quebec, Canada) and used to calculate root length density (cm root/cm^3 soil), root mass density (g/cm^3) and average root diameter (mm).

Treatment Application

Each of 50 trees was randomly assigned to one of five experimental treatments prior to treatment application on August 19, 2005. Treatments included Air Spade® tillage (AS), Mulch (M), Fertilization (F), Root Invigoration™ (AFM) and Control (C). The soil surrounding all trees was treated with Roundup Pro herbicide (15.5 ml per 1 L) (Monsanto Company, St. Louis, MO) in a 1.5 m (5 ft.) diameter ring from the trunk 14 days prior to treatment application to eliminate dense turf. Vegetation control was maintained with Roundup Pro throughout the experiment.

Trees receiving the AS treatment underwent turf removal of the upper 2.5-5.0 cm (1-2 in.) of thatch and turf using a Ryan Jr. sod cutter (Jacobson, A Textron Company, Charlotte, NC) followed by soil tillage in a 1.5 m (5 ft.) radius around the trunk. Soil was tilled to a depth of 15-20 cm (6-8 in.) using the Air Spade® series 2000 (Concept Engineering Group, Verona, PA).

Trees receiving the M treatment were mulched to a depth of 5-7.5 cm (2-3 in.) in a 1.5 m radius around the trunk using 0.45 m^3 (16 $ft.^3$) of bagged shredded hardwood mulch. Trees receiving the F treatment received a surface application of 1.3 kg (2.8 lbs.) of pelletized dolomitic limestone, 680 g (1.5 lbs.) Bartlett Boost Granular 24-7-7 (also includes micronutrients S, Ca, Fe, Cu and Zn) fertilizer and 2.67 oz (0.33 cup) manganese chelate per tree in a 1.5 m radius around the trunk. These applications were based on the analysis of a composite soil sample taken in August 2005.

Trees receiving the AFM treatment received turf removal and Air Spade® tillage as described previously. The tilled area was then amended with 0.28 m^3 (10 $ft.^3$) of composted cow manure, 1.3 kg (2.8 lbs.) of pelletized dolomitic limestone, 680 g (1.5 lbs.) Bartlett Boost® Granular and 2.67 oz (.33 cup) manganese chelate per tree in a 1.5 m radius around the trunk. All of these amendments were homogenized into the loosened native soil with the Air Spade®, and the treated area was mulched to a depth of 5-7.5 cm using 0.45 m^3 of shredded bark.

Control trees received no soil treatments other than herbicide. All trees received approximately 30 L (8 gal.) of water immediately following treatment application and again on 8/27/05 and 9/14/05.

Anderson, SC

Site characterization and background data

The second experimental site was located at the Anderson Sports and Entertainment Center (ASEC) in Anderson, SC. The ASEC is a public park, sports field and civic center complex that is highly trafficked by area residents; the local government has attempted to establish red maples in these areas. Due to the proximity to Clemson University, this site was subjected to a more intense data collection regime than other sites. Several groups of trees in the ASEC were selected for use in this study. The first group included 30 red maples located along the sidewalks leading to the civic center with an average dbh of 12.7 cm (5 in.). At the time of treatment application, these trees exhibited poor growth and thin, chlorotic canopies. The second group included five recently-planted red maples with thin, chlorotic canopies, a moderate amount of limb dieback and an average dbh of 7.6 cm (3 in.). The third group of trees included 15 red maples planted along a parking lot and sidewalk near the sports fields with an average dbh of 10.2 cm (4 in.). The trees within this group had much healthier canopies than those in the other two groups, with very little chlorosis or canopy dieback. All three groups were growing in heavily compacted clay.

In September 2005, baseline data for mean foliar chlorophyll content, foliar nutrient content, dbh, soil nutrient content and visual health rating were collected as described for the Boston site. Soil bulk density and root length density were measured at the time of treatment application in November 2005 and analyzed as previously described.

Treatment Application

Treatments were assigned in a randomized complete block design consisting of 10 replicate blocks with each treatment randomly assigned to one tree per block. Blocks were established based on tree group and visual ratings within groups. Turf surrounding experimental trees was killed with herbicide approximately two months prior to treatment application as previously described. This, coupled with sparse turf coverage near the trees, obviated the need for removal with a sod cutter.

Because of long-term seasonal drought, application of water was required to prepare the soil for air-spade treatments. All trees received 106 L (28 gals.) of water. Trees receiving AS and AFM treatments received half of the water injected 15 cm beneath the soil surface prior to treatment application and half as a drench following treatment application. All other treatments received the entire volume injected below the soil surface.

Treatments were applied as described for the Boston site, with the exception that fertilizer rates and materials reflected the results of soil analyses performed at this site. Trees receiving AFM and F treatments in-group one were amended with 375 g (0.75 lb.) Bartlett Boost® Granular, 565 g (1.18 lbs.) granular Sulfur and 265 g (0.55 lb.) Magnesium Sulfate per tree. Trees receiving AFM and F treatments in groups two and three were amended with 470 g (1 lb.) Bartlett Boost® Granular and 1.4 Kg (2.9 lbs.)

pelletized dolomitic lime per tree. Additional supplemental irrigation was not necessary, as trees were dormant and frequent rainfall ensued.

In November 2005, one clear butyrate observation tube (minirhizotron) was installed beneath each tree at an angle of 30° from the vertical. The tubes were placed approximately 0.75 m from the trunk. They were 77 cm (30 in.) in length and 5.5 cm (2.2 in.) in outer diameter. Bottoms of the tubes were sealed with acrylic plugs. Light penetration and radiant heating were prevented by wrapping the tops of the tubes in black electrical tape, sealing them with rubber stoppers and covering them with tan aluminum cans.

Root Imaging and Processing

Roots that grew against the surface of the minirhizotron tubes were videotaped at approximately two-week intervals during the 2006 and 2007 growing seasons using a miniaturized camera system and portable laptop computer (BTC 2 and BTC I-CAP, Bartz Technology, Santa Barbara, CA). Image capture was reduced to monthly intervals during the winter, as prior observations indicated that there was little root activity during that time. Imaged frames were archived using ICAP software (Bartz Technology, Santa Barbara, CA). Images of individual roots as they appeared on successive dates were reviewed and information on root lifespan and life history was collected. Images were analyzed using software developed by Clemson University to quantify root attributes such as root length, diameter, color, and birth and death rates (http://www.ces.clemson.edu/~stb/rootfly).

Additional Parameters

The effects of these treatments on plant water status was quantified bi-weekly during the 2006 and 2007 growing seasons by measuring predawn leaf water potential with a 3005-series portable plant water status console (Soilmoisture Equipment Corp., Santa Barbara, CA). Soil moisture levels were measured weekly using the TRASE Time Domain Reflectometry system I (Soilmoisture Equipment Corp., Santa Barbara, CA). Chlorophyll fluorescence measurements were performed during both growing seasons using the Handy PEA Portable Fluorescence Measurement System (Hansatech Instruments, Norfolk, England).

Myrtle Beach, SC

Site Characterization and Background Data

The third site was located in Myrtle Beach, SC, where a planting of red maples lines the Robert M. Grissom Parkway. These trees have an average dbh of 6.1 cm (2.4 in.) and were planted by the city of Myrtle Beach at different times as funding allowed. They received no fertilizer or pesticide applications after planting. Soils at the site are sandy, and trees receive periodic irrigation from an automated overhead system. Prior to our experiment, most trees had a light infestation of gloomy scale (Melanaspis tenebricosa), and 2% horticultural oil (Lesco Horticultural Oil, Lesco, Inc., Cleveland, OH) was applied in November 2005 to suppress this population.

In October 2005, baseline data for mean foliar chlorophyll content, foliar nutrient content, dbh, soil nutrient content and visual health rating were collected as described previously. Soil bulk density and root length density samples were collected at the time of treatment application in November 2005 and analyzed as previously described.

Treatment Application

Treatments were assigned in a randomized complete block design consisting of 10 replicate blocks with each treatment randomly assigned to one tree per block. Blocks were established based on tree group and visual ratings within groups. The treated radius of these trees was generally free of turf and vegetation, so herbicide and/or turf removal was necessary on only one tree. For this tree, turf was removed with hand tools.

The fertilizer rates and materials were based on soil samples collected and analyzed in October 2005. Those trees receiving AFM and F treatments were supplied with 565 g (1.2 lbs.) Bartlett Boost® Granular, 1.3 Kg (2.8 lbs.) granular sulfur, 455 g (1 lb.) magnesium sulfate and 300 ml (1.25 cups) manganese chelate. All other aspects of treatment application were identical to previous sites.

Pittsburgh, PA

Site characterization and background data

The final site was located in suburban Pittsburgh, PA at The Club at Nevillewood golf course. Here, red maples with an average dbh of 15.7 cm (6.2 in.) were planted along fairways and in areas of rough at various stages of course development. Many trees had been subjected to mechanical wounding during planting or by maintenance equipment. Most trees had vegetation-free rings (40-50 cm in diameter) surrounding the trunk but were otherwise surrounded by turf. Trees received supplemental irrigation through the golf course overhead irrigation system. No fertilizer or pesticide products had been directly applied to the trees, although they had received products applied to the turf as a byproduct of their location.

In January 2006, baseline data on soil nutrient content, dbh, soil bulk density and root length density were collected as previously described. Foliar chlorophyll content, foliar nutrient content, and visual health ratings were not collected because the trees were dormant.

Treatment Application

Treatments were assigned in a randomized complete block design consisting of 10 replicated blocks with each treatment randomly assigned to one tree per block. Blocks were established based on tree location and size. Treatments were applied in February 2006. The treatment radius for trees receiving F, M and C treatments was treated with Roundup Pro herbicide (59 ml per 3.8 L) to eliminate turf competition. Manual removal of competing turf within the treated radius was required and performed with hand tools for trees receiving AS and AFM treatments because there was not sufficient time for turf mortality following a herbicide treatment. No irrigation was necessary prior to treatment, as the soil was near field-capacity. Two inches of snow fell on the day following treatment application, obviating the need for post-treatment irrigation.

The fertilizer rates and materials were applied based on soil samples collected and analyzed in January 2006. Trees receiving AFM and F treatments were supplied with 262 g (0.5 lb.) Bartlett Boost® Granular, 3.5 Kg (7.8 lbs.) pelletized gypsum, 1.1 Kg (2.4 lbs.) granular sulfur and manganese, and 169 g (0.35 lb.) magnesium\sulfate. Trees receiving M and AFM treatments were mulched with 18 cu. ft. of mulch. All other aspects of treatment application were identical to previous sites.

Subsequent data collection visits were made to each site according to the schedule in Table 1.5. Samples were collected and processed according to the procedures outlined previously. Bulk density measurements were replaced by soil strength measurements due to difficulty of collecting accurate post-treatment soil volumes in the decompacted soils. Soil strength values were obtained using a Clegg Impact Hammer (Dr Baden Clegg Pty Ltd., Western Australia); three readings per tree were averaged to obtain the Clegg Impact Values for each tree.

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CHAPTER III

SOIL RESPONSE

Abstract

The Root Invigoration™ (AFM) process involves soil decompaction with an air tool, amendment with organic matter and prescription fertilizer, and mulching. The treatment is intended to provide a soil environment more conducive to fine root function. In the current study, we measured changes in soil chemistry and physical properties in response to RI and its individual components. The treatments were: 1) Root Invigoration™, 2) mulch only, 3) fertilization only, 4) Airspade® tillage only, and 5) an untreated control. The experiment was conducted from 2005-2007 at urban sites in Anderson, SC; Boston, MA; Myrtle Beach, SC and Pittsburgh, PA. Soil strength was initially reduced by Airspade®, mulch and AFM; however only AFM-treated soils sustained this reduction over two seasons. Across all locations, soil organic matter content was increased with AFM and mulching. The levels of six soil nutrients were increased by Root Invigoration™, while one nutrient was increased by an individual treatment.

Introduction

The urban environment is often stressful to trees, and research suggests that much of this stress is caused by soil factors. Soil characteristics such as low porosity, poor aeration, and increased moisture fluctuations can lead to poor tree development (Watson et al., 1996). Urban soils have frequently been disturbed through the processes of mixing, filling and contamination (Craul, 1985). They tend to be highly compacted, with bulk densities higher than those of similar soils in nearby forested areas (Close et al., 1996a). While forest soils have a well-developed humus layer, urban soils typically lack an upper organic horizon (Fraedrich and Ham, 1982). Compaction increases soil resistance to root penetration and limits root system development in urban soils (Alberty et al., 1984).

It is challenging to improve soil physical properties within the root zone of established trees because traditional soil decompaction methods such as mechanical tillage can cause additional root system damage (Watson et al., 1996). Homeowners, municipalities and tree care companies would all benefit from successful strategies for improving conditions for root growth in urban soils. Unfortunately, few effective treatment options exist. Upon reviewing traditionally accepted practices in the tree care industry, Day and Bassuk (1994) concluded that arboricultural techniques that reduce compaction merit further exploration.

A variety of pneumatic decompaction devices have been developed to physically break up compacted soils beneath landscape trees. Such equipment is designed to fracture compacted soil layers by introducing pressurized air or nitrogen (Smiley et al., 1990). The resulting fractures are often filled by fertilizer, amendments and/or water. Soil physical properties have not been consistently improved by the use of pneumatic injection devices (Hascher and Wells, 2007; Rolf, 1992; Smiley, 2001; Smiley et al., 1990).

The Root Invigoration™ process, developed and patented by the F.A. Bartlett Tree Expert Co., is designed to decompact and aerate the soil with minimal root disturbance while simultaneously incorporating organic matter and fertilizer into the root zone. Here we report changes in soil chemical and physical properties associated with the Root Invigoration™ process and its individual components beneath red maples (*Acer rubrum*) at four urban locations.

Materials and Methods

Site Characterization

The study was conducted on 200 red maple trees at four urban locations: Anderson, SC (city park and recreation facility); Myrtle Beach, SC (street tree plantings); Boston, MA (college campus) and Pittsburgh, PA (golf course). Soil textures ranged from sandy clay in Anderson to sand in Myrtle Beach (Table 3.1). Bulk densities ranged from 1.14 ± 0.04 g/cc in Boston to 1.74 ± 0.04 g/cc in Myrtle Beach. None of the sites were compacted beyond the growth-limiting bulk density for their respective texture (Daddow and Warrington, 1983). However, these growth-limiting bulk densities must be observed with caution as soil moisture and species responses may differ and limit the application of these thresholds (Daddow and Warrington, 1983).

Pretreatment Soil Data

Prior to treatment application, composite soil samples were collected from the upper 15 cm (6 in.) of soil beneath 6-8 trees at each site and analyzed by A&L Analytical Laboratory (Memphis, TN) to determine soil pH, CEC, organic matter content, and

Table 3.1. Pre-treatment soil classifications. Multiple samples within sites revealed identical textures and were averaged for the table. Anderson was the exception and those values are displayed separately. *n*=3 for Anderson, *n*=2 for Pittsburgh, *n*=3 for Myrtle Beach and *n*=3 for Boston. Dominant NRCS classifications are displayed.

Sample	% sand	% silt	% clay	Texture	NRCS soil name
Anderson (group 1)	60	22	18	Sandy Loam	Hiwassee sandy loam
Anderson (group 2)	46	18	36	Sandy Clay	Hiwassee sandy loam
Anderson (group 3)	58	18	24	Sandy Clay Loam	Hiwassee sandy loam
Myrtle Beach	93	3	4	Sand	Brookman loam & Meggett loam
Pittsburgh	32.9	44.7	22.4	Loam	Dormont silt loam
Boston	70.8	22.6	6.7	Sandy Loam	Walpole fine sandy loam & Hinckley sandy loam

mineral nutrient concentrations (Table 3.2). Nutrient data from these samples were further analyzed with the Bartlett Tree Research Laboratories soil recommendations program to create a prescription fertilizer program to comply with ANSI A300 standards and adjust pH within the 5.0-6.0 range (Table 3.3). In general, the Pittsburgh soil had higher nutrient levels compared to the other sites.

Experimental Design and Treatment Application

Five treatments, mulch (M), fertilizer (F), Airspade® tillage (A), Root Invigoration™ (AFM) and control (C), were applied to ten replicate trees at each site, for a total of 50 experimental units per site. In Boston, a completely randomized design was used. A randomized complete block design was used at the Anderson, Myrtle Beach and Pittsburgh sites to account for site variability. The treatments were applied in August 2005 in Boston, November 2005 in Anderson, November 2005 in Myrtle Beach and February 2006 in Pittsburgh.

Table 3.2. Chemical and physical properties of pre-treatment soil collected from each research site. Within-site means are followed by ± 1 standard error.

Parameter	**Anderson**[1]	**Boston**[2]	**Myrtle Beach**	**Pittsburgh**
ENR[3] (kg/ha)	85.5 ± 14.6	114	54.7 ± 9.5	74.4 ± 2.4
Soil P (ppm)	12.3 ± 2.6^{c}	288^{a}	38.3 ± 3.0^{c}	115.3 ± 20.2^{b}
Soil K (ppm)	138.7 ± 14.4^{b}	87^{c}	43.5 ± 7.4^{d}	276.7 ± 5.2^{a}
Soil Mg (ppm)	112.7 ± 23^{b}	99^{b}	64.3 ± 8.7^{b}	452.7 ± 27.9^{a}
Soil Ca (ppm)	942.3 ± 274.3^{b}	977b	3648.5 ± 967.8^{ab}	5133.3 ± 768.4^{a}
Soil Na (ppm)	13.6 ± 0.3^{c}	39^{b}	30.3 ± 7.0^{ab}	85.3 ± 3.3^{a}
Sol. Salt (ppm)	0.3 ± 0	0.3	0.3 ± 0	0.2 ± 0.03
Soil Fe (ppm)	51.7 ± 3.7^{c}	295^{b}	134.5 ± 24^{c}	478.7 ± 31.9^{a}
Soil Mn (ppm)	104.3 ± 39.8^{b}	24^{b}	7.8 ± 1.4^{b}	312 ± 21.2^{a}
Soil Cu (ppm)	1.6 ± 0.3^{c}	9.6^{a}	0.6 ± 0.1^{c}	4.0 ± 0.5^{b}
Soil Zn (ppm)	2.7 ± 1.2^{b}	14.4^{a}	2.5 ± 0.5^{b}	5.2 ± 0.5^{b}
Soil OM (%)	2.8 ± 0.9	4.6	1.6 ± 0.4	2.0 ± 0.1
Soil CEC (meq/100g)	7.7 ± 1.1	9.6	19.0 ± 5.0	17.2 ± 1.8
Soil pH	5.7 ± 0.4	5.5	7.9 ± 0.1	6.8 ± 0.07
Bulk Density (g/cc)	1.41 ± 0.02b	1.14 ± 0.04d	1.74 ± 0.04a	1.25 ± 0.03c

[1] Chemical properties based on: Anderson n=3; Boston n=1; Myrtle Beach n=4; Pittsburgh n=3. Bulk density based on: n=50 at all sites.

[2] Post hoc analysis cannot be performed because *n*=1

[3] Estimated Nitrogen Release based on soil organic matter

Table 3.3. Fertilizer products applied to each AFM and fertilizer-treated soil area (7.1 m^2; 76.4 ft.^{2}).

Product	Analysis	Manufacturer	Anderson (group #)	Boston	Myrtle Beach	Pittsburgh
Boost Granular	24-7-7 S 6% Ca 1% Fe .10% Cu .05% Zn .05%	F.A. Bartlett Tree Expert Co. Stamford, CT	375 g (1) 470 g (2 & 3)	1.3 kg	565 g	262 g
Manganese Chelate	5% Mn 2% S	Growth Products LTD. White Plains, NY		79 ml	300 ml	
Tiger 90	0-0-0-90 S	Tiger-Sul Products Co Calgary, AB	565 g (1)		1.3 kg	
Epsom salt	100% $MgSO_4$	Top Co Associates LLC Skokie, IL	265 g (1)		455 g	169 g
Pelletized dolomitic lime	21% Ca 11% Mg	ASC Mineral Processing Allerton, IL	1.4 kg (2 & 3)			
Pelletized gypsum	20% Ca 16% S	ASC Mineral Processing Allerton, IL				3.5 kg
Disper-Sul plus Iron and Manganese	80% S 3.5% Fe 1.5% Mn	Martin Resources, Inc. Odessa, TX				1.1 kg

The area surrounding all trees was treated with Roundup Pro herbicide (Monsanto Company, St. Louis, MO) in a 1.5 m (5 ft.) diameter ring from the trunk at least 14 days prior to treatment application to eliminate competing vegetation, and weed control was maintained throughout the experiment with Roundup applications.

In Boston, it was necessary to remove the turf using a Ryan Jr. sod cutter (Jacobson, A Textron Company, Charlotte, NC) for trees receiving the A and AFM treatments due to the extensive root system of the turf that remained after herbicide application. Some tree fine roots were likely damaged during this process.

Soils receiving the M treatment were mulched to a depth of 5-7.5 cm (2-3 in.) in a 1.5 m (5 ft.) radius around the trunk using 0.45 m^3 (16 $ft.^3$) of bagged, shredded hardwood mulch. Soils receiving the F treatment were fertilized with the prescribed materials (Table 3.3) applied to the soil surface as a granular product or drench within the 1.5 m (5 ft.) radius. Soils receiving the A treatment were air-tilled to a depth of 15-20 cm (6-8 in.) using the Air Spade® series 2000 (Concept Engineering Group, Verona, PA) in a 1.5 m (5 ft.) radius around the trunk. Controls received no amendment or tillage treatment, but were maintained with a 1.5 m (5 ft.) radius vegetation-free zone.

The AFM treatment began with Airspade® tillage as described above. Soils were then amended with 0.28 m^3 (10 $ft.^3$) of bagged, composted cow manure and prescription fertilizer as in F treatment. Amendments were applied to the 1.5 m (5 ft.) radius and incorporated into the loosened soil profile with the Airspade®. Finally, amended soil received a mulch layer as described for the M treatment.

Immediately after treatment application, 30L (8 gal.) of irrigation was applied to the 1.5 m (5 ft.) treatment radius of all trees at the Boston and Myrtle Beach sites. The Boston site received identical irrigation applications at one and three weeks post-treatment due to dry conditions. Because of long-term seasonal drought in Anderson, water applications were required to prepare the soil for air-spade treatments. At this site, all soils received 106 L (28 gals.) of water injected approximately 15 cm (6 in.) beneath the soil surface. Trees receiving AS and RI treatments were given split applications with half of the water injected beneath the soil surface prior to treatment application and half as a drench following treatment application. In Pittsburgh, two inches of snow fell on the day following treatment application, obviating the need for post-treatment irrigation.

Sample Collection and Processing

Soil bulk density was measured by collecting a soil core 5.77 cm (2.3 in.) in diameter from beneath each tree approximately 0.75 m (2.5 ft.) from the trunk. These cores were trimmed to 7.6 cm (3 in.) in length, and turf, leaf litter and organic matter layers were removed from the tops. They were stored at 5°C (41°F) in wax-lined paper bags for less than one week before processing. Cores were transferred to aluminum trays and dried for seven days at 65°C (149°F) and weighed to calculate bulk density (g/cc).

A Clegg impact hammer was used to measure post-treatment soil strength at three locations beneath each tree in the spring of 2006 and 2007. The Clegg Hammer drops a weighted accelerometer from a standard height and measures its deceleration upon impact with the soil surface. This measurement is reported as a Clegg Impact Value

(CIV). Soils with high CIV have greater soil strength and may be more resistant to root penetration (Waltz et al., 2000).

CIV measurement was preferable to bulk density measurement for assessment of post-treatment soil compaction due to the inaccuracy of bulk density coring on decompacted and high organic matter soils. Soils become extremely friable after Airspade® treatment, causing bulk density cores to crumble and collapse during extraction. Furthermore, loosened, mulched, and/or amended soils tend to recompact during the process of core sampling.

One composite soil sample from 3 locations within the treated radius of each tree was collected in spring 2006 and 2007 for analysis of soil nutrient content. These samples were analyzed by the Clemson University Agricultural Services Laboratory for soil pH, CEC, organic matter content (loss on ignition method), and mineral nutrient concentrations.

Soil Moisture

In June 2006 in Anderson, five Time Domain Reflectometry waveguides (Soilmoisture Equipment Corp., Santa Barbara, CA) were buried 15 cm (6 in.) below the soil surface. Two were placed under mulched soils and thee were placed under bare soils. Soil moisture content was collected weekly using the Trace System I (Soilmoisture Equipment Corp., Santa Barbara, CA).

Statistical Analyses

The effects of treatment, time, location and their interactions on soil parameters were analyzed using a generalized linear model (SAS PROC GLIMMIX, SAS version 9.1; SAS Institute, Cary, NC). Data met normality and equal variance assumptions. All mean separations were performed with Fischer's least significant difference, and all analyses were evaluated at the $\alpha = 0.05$ significance level.

Results

Overall Soil Results

Across all sites, AFM treatment reduced soil strength by an average of 82% in 2006 ($p < 0.0001$) and 24% in 2007 ($p = 0.0043$). Airspade® and mulch treatments also significantly reduced soil strength in 2006 (23% and 19%, respectively), but in 2007 the strength of these soils had returned to control levels. At no time did fertilizer reduce soil strength relative to control (Fig. 3.1).

Across all sites and dates, soils that received the AFM and mulch treatments had significantly higher organic matter than control soils ($p < 0.01$), while Airspade® treated soils had significantly lower organic matter than controls ($p = 0.016$; Fig. 3.2).

Across all sites and dates, phosphorus, potassium, magnesium, manganese, boron, and zinc concentrations were significantly higher in AFM treated soils than control soils ($p < 0.01$; Fig. 3.3). Extractable phosphorus levels were 73% and 48% higher for AFM than control and fertilizer soils, respectively. Soils that received only fertilizer were lower than AFM soils in all aforementioned nutrients except manganese and never

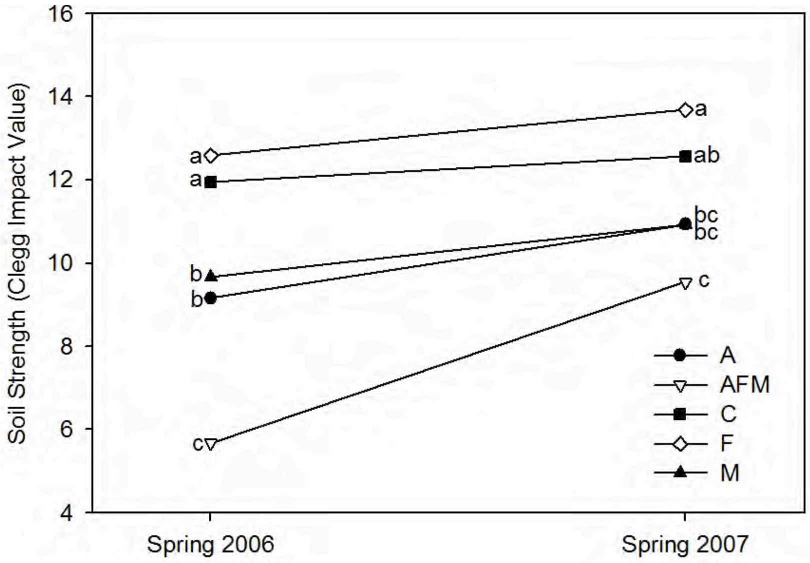

Figure 3.1. Soil strength measured in spring 2006 and 2007. Data from all sites have been combined (n=40 for each group). Within each season, treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure (α=0.05).

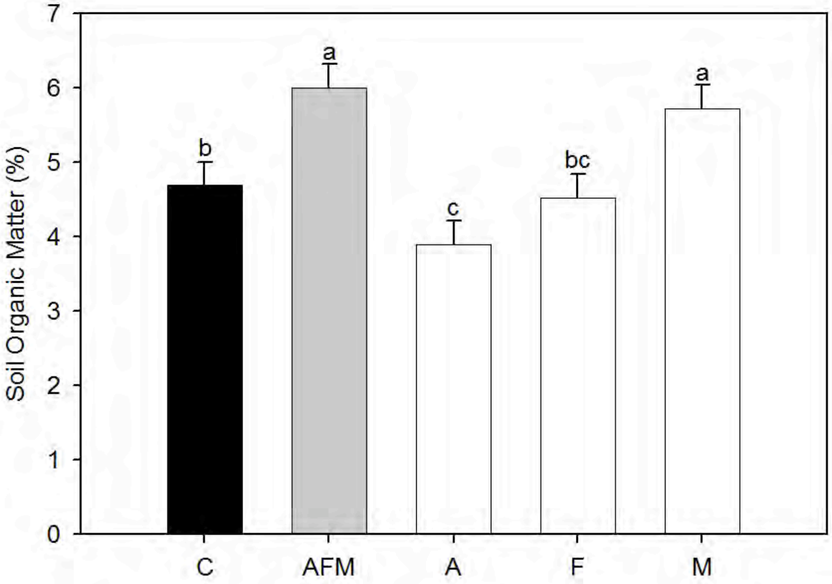

Figure 3.2. Percent organic matter of soils in spring 2007 treated with 4 different amelioration techniques (n=40 for each treatment group). Data from all sites have been pooled. Error bars represent one standard error of the mean. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure (α = 0.05).

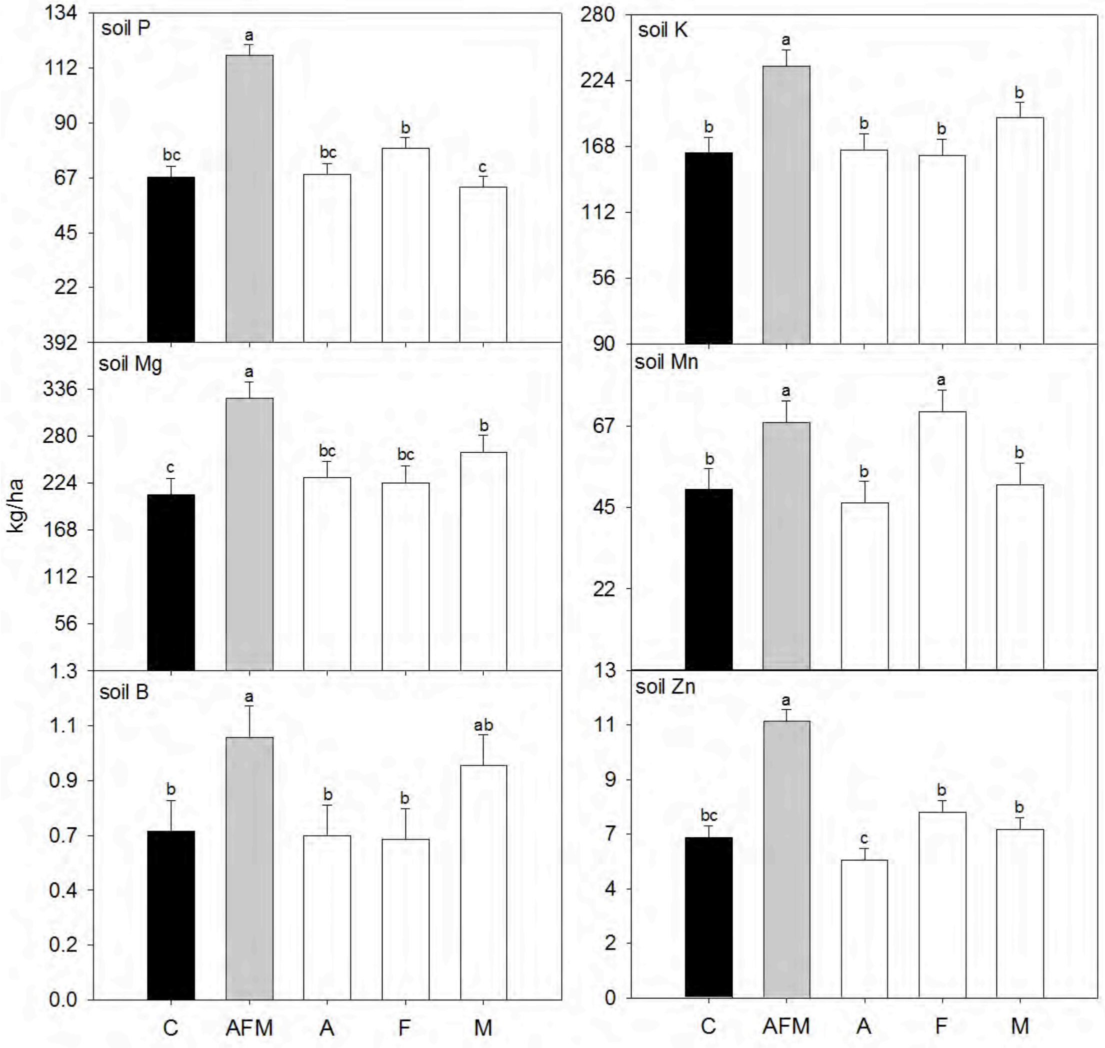

Figure 3.3. Phosphorus, potassium, magnesium, manganese, boron and zinc content of treated soils. Data from all sites and sampling dates have been combined (n=80 for each treatment group). Error bars represent one standard error of the mean. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.05$).

differed from control soils. In spring 2007, copper levels in fertilized soils were higher than AFM, control and mulched soils (Fig. 3.4).

Soil moisture was measured at the Anderson, SC site only. Averaged across all measurement dates, mulched soils (i.e., the AFM and M treatments) had significantly higher volumetric soil moisture content than unmulched soils (Fig. 3.5). During the 2006 growing season, soil moisture levels in the mulched treatments were significantly higher than in the unmulched treatments on three dates. In 2007, there were seventeen such occurrences. During August 2007, upstate South Carolina was experiencing a 30 cm (11.8 in.) annual precipitation deficit and was considered to be under extreme drought by the National Weather Service Palmer Drought Severity Index (NWS, 2007).

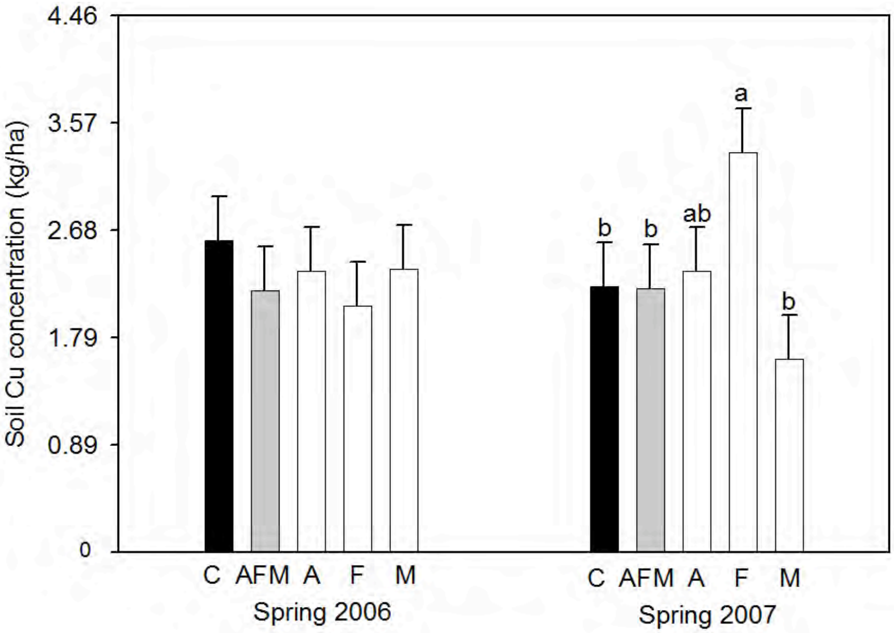

Figure 3.4. Copper content of treated soils within sampling dates. Data from all sites have been combined (n=40 for each treatment group). Error bars represent pooled standard error of the mean. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.05$).

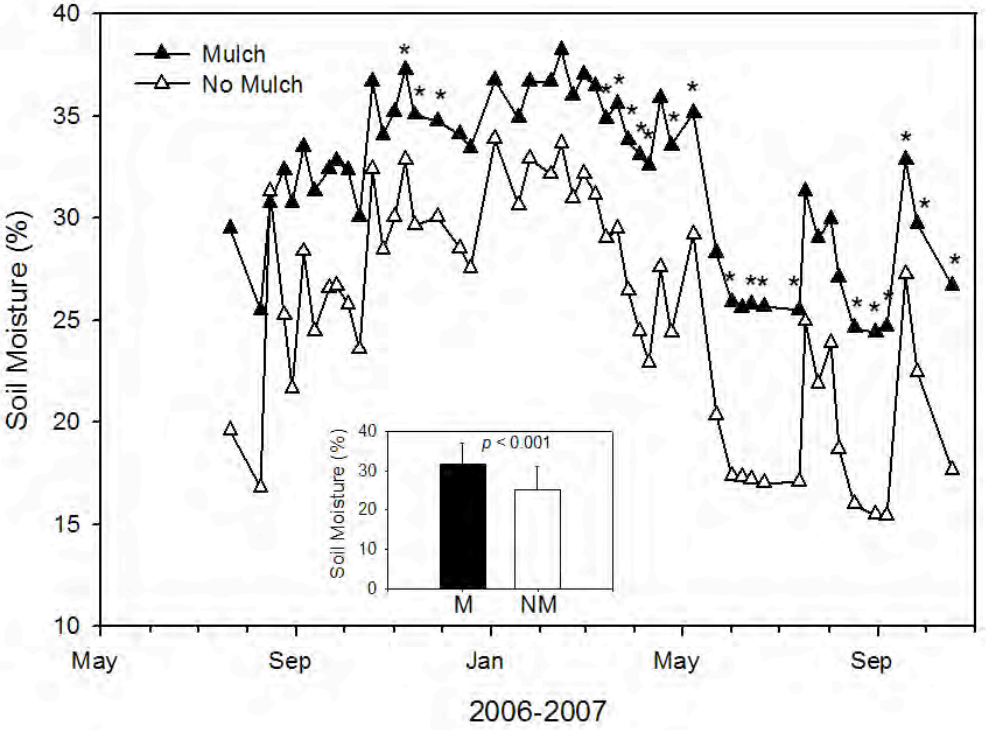

Figure 3.5. Percent soil moisture throughout 2006 and 2007 seasons in Anderson (n=2 for mulch and n=3 for no mulch). Inset panel shows overall means for two seasons. *Denotes a significant difference in treatment means at α=0.05 using Fisher's multiple comparisons procedure.

Discussion

Soil Strength

AFM treatment of compacted soil resulted in lower soil strength for two years; Airspade® and mulch treatments only provided significant decompaction for one season after treatment. This result clearly demonstrates the benefits of organic matter amendment and surface mulching in preventing recompaction of soils loosened with the Airspade®. Although AFM and mulch-treated soils had similar organic matter content, mulch alone did not provide significant reductions in soil strength after two growing seasons.

Reductions in soil strength can improve conditions for root development (Alberty et al., 1984; Jones, 1983). Root dry weights and root penetration of seedlings can be reduced in compacted soils (Conlin and Driessche, 1996; Heilman, 1981), and roots may also be thicker and more branched due to the physical resistance they encounter (Day and Bassuk, 1994; Pittenger and Stamen, 1990). This can lead to drought and/or nutrient stress due to the reduced ability of roots to exploit larger soil volumes (Marschner, 2002).

In addition to increasing soil strength, soil compaction also reduces the volume of air-filled soil macropores (Corns, 1988). When soil is compacted, large macropore space accounts for most of the soil volume lost, with some of these voids being shifted into micropore space (Craul, 1992). This can result in anaerobic conditions and root tissues must rely on inefficient fermentative metabolism for energy (Pan and Bassuk, 1985; Taiz and Zeiger, 2002).

Compaction not only affects soil aeration, but also influences soil water dynamics since these two are coupled. Compacted soils are subject to waterlogging, which can also lead to impaired root functioning (Percival and Keary, 2008). With a shift to a greater proportion of micropores, soil water will also be held under greater tension as a soil dries and be more difficult or impossible for plant roots to access it (Taiz and Zeiger, 2002).

Soil Organic Matter

AFM and mulched trees had higher levels of soil organic matter than controls and other treatments. However, it must be noted that we did not determine the extent to which the organic matter moved into the soil profile. It is possible that the organic additions are only occurring on the soil surface of the M soils. These data confirm

Watson's findings that surface mulch layers can lead to increases in soil organic matter (Watson, 1988). This occurs over time as the organic mulch decomposes and improves soil structure (Harris et al., 2004). Craul (1985) states that these increased levels of organic matter are a major source of energy for soil organisms and lead to a healthy soil environment for root growth. As organic tissues are decomposed by soil microbes, energy is used and complex compounds are transformed into simple compounds and mineral nutrients for root uptake (Craul, 1992; Harris et al., 2004). Organic matter provides the food source and environment for these microorganisms to flourish.

Airspade® tillage alone resulted in a decrease in soil organic matter. Tillage practices have long been associated with decreases in soil organic carbon (Gal et al., 2007). Organic matter is allowed to accumulate with minimal soil disturbance due to the reduction in decomposition by soil microbes (Gal et al., 2007; Motta et al., 2007). However, when soil is mixed, microbes have greater contact with the organic compounds and breakdown is enhanced (Cookson et al., 2008). AFM may have accelerated decomposition as well, but was compensated for with the addition of the composted material as part of the program.

If increased levels of soil organic matter are the only goal of a management program, simply applying a mulch layer to the soil surface may be the most cost-effective method. However, we have no data showing the distribution of this organic matter throughout the root zone. The deposition of the organic matter in the mulched soils is likely only occurring in the upper few centimeters of the soil profile, whereas the AFM treatment incorporates it in the upper 15-20 cm (6-8 in.).

Soil Nutrients

Levels of phosphorus, potassium, magnesium, manganese, boron and zinc were all increased in AFM-treated soils compared to control. These nutrients, excluding manganese, were not significantly increased by surface application of fertilizer alone.

Sub-surface incorporation of fertilizer into the upper soil layers has been recommended for low solubility minerals or when roots are not near the surface due to elevated surface temperatures or cultivation (Harris et al., 2004). However, Gilman et al. (2000) report that subsurface applications provided no greater growth benefit than surface applications, a conclusion that is echoed by Struve (2002).

The incorporation of fertilizer in the context of a complete soil decompaction process has not previously been studied. Our data corroborate the statement by Harris, et al (2004). The incorporation of fertilizer products as part of the AFM treatment created significantly higher levels of select nutrients in the soil than the application of the same products to the soil surface. The nutrient levels were undoubtedly enhanced with the incorporation of the additional organic matter.

It is important to note that nutrient uptake is a function of soil structure and water availability in addition to soil nutrient levels. All 3 of these factors are improved with AFM. Nutrient uptake is an energetic process that can demand up to 36% of the plant's total ATP utilization, so factors that impact respiration will also affect nutrient uptake (Marschner, 2002). As previously mentioned, aerobic environments support efficient respiration pathways in roots, so improvements in soil macroporosity allow for more energy efficient nutrient uptake.

Nutrient uptake also depends on soil water for ion availability. Mineral ions are transported to the root surface in the soil solution (Taiz and Zeiger, 2002). Ions then move into the intercellular space of root tissue to be taken up into living cells. When the soil contains a large percentage of micropores, tightly held soil water and nutrients are unavailable for uptake. The reduced soil strength and increased nutrient levels of AFM soils should result in enhanced water and nutrient availability.

Soil Moisture

Soil moisture was significantly higher beneath mulched than unmulched trees on numerous dates throughout an extremely arid 2007 growing season in Anderson, SC (the only site where soil and tree water relations were measured). The mean soil moisture percentage across both growing seasons was 26% higher for mulched versus unmulched soils. These data corroborate other studies on the benefits of maintaining a proper mulch layer (Fraedrich and Ham, 1982; Himelick and Watson, 1990; Iles and Dosmann, 1999; Litzow and Pellett, 1983; Watson, 1988). Watson (1988) observed a 9% increase in soil moisture at the 0-7.5 cm depths in mulched soil compared to bare soil, while Hemelick and Watson (1990) saw a 63% increase beneath mulch compared to turf cover.

Site Differences

When considered alone, soil strength in Boston was not significantly improved by any treatment (data not shown). The mean pre-treatment bulk density at this site (1.14 ± 0.04 g/cc) was lower than other sites, indicating that decompaction treatments may be more effective on more heavily compacted sites.

Conclusions

Soil strength, organic matter content, the levels of 6 mineral nutrients and soil moisture were improved in AFM-treated soils. Although soil strength was temporarily improved by other treatments, only AFM soils were able to maintain this reduction for two seasons following treatment. With regard to organic matter, similar results may be achieved by mulching the soil surface; however, the other reported parameters benefited more from the AFM treatment than any individual component of the program. Over time, the addition of organic matter through mulching alone may improve other soil parameters, but AFM provided those benefits quickly. Applying fertilizer to the soil surface was ineffective compared to incorporation of fertilizer as part of AFM. Maintaining a proper mulch layer alone or as part of the AFM treatment increased soil moisture.

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CHAPTER IV

TREE RESPONSE

Abstract

The Root Invigoration™ process involves soil decompaction with an air tool, amendment with organic matter and prescription fertilizer, and mulching. In the current study, we measured changes in tree response to this process and its individual components. Treatments included Root Invigoration™ (AFM), mulch only (M), fertilization only (F), Airspade® tillage only (A), and an untreated control (C). The experiment was conducted from 2005-2007 at four urban sites: Anderson, SC; Boston, MA; Myrtle Beach, SC and Pittsburgh, PA. Condition ratings were significantly higher in AFM trees than control trees by the end of 2007. In two locations, increases in dbh were also greater for AFM trees. At the end of 2006, estimated chlorophyll concentrations were higher in AFM trees than in the A or M treatments. Foliage of AFM trees had higher levels of phosphorus and potassium than foliage of fertilized trees. Mulched soils (both AFM and M) frequently had higher soil moisture content. During a drought period in 2007, pre-dawn leaf water potential was higher for M trees on two dates and for AFM trees on one. Although there were differences in root length density (cm root/cm^3 soil) among treatments in 2006, there were none in 2007. Mean root diameter was increased with fertilization.

Introduction

Urban trees experience significant environmental stress, frequently related to soil factors. Most urban soils have been disturbed by mixing, filling and contamination, and they contain low levels of nutrient-rich organic matter (Craul, 1985). Such soils also tend to be highly compacted, with bulk densities higher than those of similar soils in nearby forested areas (Close et al., 1996a). Compaction increases soil resistance to root penetration and limits root system development (Alberty et al., 1984), while low porosity, poor aeration, and increased soil moisture fluctuations impair root function and tree growth (Watson and Kelsey, 2006; Watson et al., 1996). Arboricultural techniques that reduce compaction and improve soil quality merit further exploration (Day and Bassuk, 1994). Unfortunately, few effective treatment options exist.

It is challenging to improve soil physical properties within the root zone without causing significant root damage in the process. Traditional soil decompaction methods such as mechanical tillage can cause additional root system damage in established trees (Watson et al., 1996). Pneumatic injection devices have been developed to physically fracture compacted soils while avoiding root damage, but neither soil physical properties nor tree performance have been consistently improved by their use (Hascher and Wells, 2007; Rolf, 1992; Smiley, 2001; Smiley et al., 1990).

Other treatment options such as vertical mulching and radial trenching appear to provide limited benefit, although they are commonly used (Day and Bassuk, 1994; Day et al., 1995; Kalisz et al., 1994; Watson et al., 1996). Extensive soil replacement programs have shown promise for increasing root density within the amended replacement zones, but don’t appear to alter root growth outside of those areas (Watson, 2002; Watson et al., 1996). Such programs have not been shown to provide significant above-ground growth benefits.

The benefits of organic mulch layers are well documented and include soil moisture retention, weed suppression, soil temperature moderation and increased water infiltration (Fraedrich and Ham, 1982; Greenly and Rakow, 1995; Litzow and Pellett, 1983). However, mulch-related changes in soil compaction and organic matter content may take years to develop (Fraedrich and Ham, 1982; Watson et al., 1996).

Trees are frequently fertilized to compensate for low nutrient levels in urban soils. In some cases, slow-release fertilizers have been shown to provide greater benefit than ammonium nitrate and urea fertilizers, but other studies have shown that all fertilizer types provide similar benefits (Gilman et al., 2000). Application methods may be more important than fertilizer type, although differences appear to be small (Struve, 2002).

The Root Invigoration™ program was developed to ameliorate multiple unfavorable characteristics of urban soils through a combination of air tillage, fertilization and mulching. This process, developed and patented by the F. A. Bartlett Tree Expert Co., is designed to decompact and aerate the soil with minimal root disturbance using an air tool while simultaneously incorporating organic matter and fertilizer into the root zone. Here we report responses of red maples (*Acer rubrum*) to the Root Invigoration™ process and its individual components at four urban locations.

Materials and Methods

Site Characterization

The study was conducted on 200 red maple trees at four locations: Anderson, SC (city park and recreation facility); Myrtle Beach, SC (street tree plantings); Boston, MA (college campus) and Pittsburgh, PA (golf course). Soil textures ranged from sandy clay in Anderson to sand in Myrtle Beach (Table 4.1). Bulk densities ranged from 1.14 ± 0.04 g/cc in Boston to 1.74 ± 0.04 g/cc in Myrtle Beach. None of the sites were compacted beyond the growth-limiting bulk density for their respective texture (Daddow and Warrington, 1983). However, these growth-limiting bulk densities must be observed with caution as soil moisture and species responses may differ and limit the application of these thresholds (Daddow and Warrington, 1983).

Table 4.1. Pre-treatment soil classifications. Multiple samples within sites revealed identical textures and were averaged for the table. Anderson was the exception and those values are displayed separately. *n*=3 for Anderson, *n*=2 for Pittsburgh, *n*=3 for Myrtle Beach and *n*=1 for Boston. Dominant NRCS classifications are displayed.

Sample	**% sand**	**% silt**	**% clay**	**Texture**	**NRCS soil name**
Anderson (group 1)	60	22	18	Sandy Loam	Hiwassee sandy loam
Anderson (group 2)	46	18	36	Sandy Clay	Hiwassee sandy loam
Anderson (group 3)	58	18	24	Sandy Clay Loam	Hiwassee sandy loam
Myrtle Beach	93	3	4	Sand	Brookman loam & Meggett loam
Pittsburgh	32.9	44.7	22.4	Loam	Dormont silt loam
Boston	70.8	22.6	6.7	Sandy Loam	Walpole fine sandy loam & Hinckley sandy loam

Sample Collection and Processing

Stem diameters at 1.4 m (4.5 ft.) above ground level (DBH) were measured at the time of treatment application and again at the end of the 2007 growing season. Mean foliar chlorophyll content was estimated by averaging SPAD meter (Minolta SPAD-502, Minolta Inc, Japan) readings from three randomly-selected leaves per tree. Foliar nutrient content was assessed by collecting approximately 100 g (3.5 oz.) of mature leaves from multiple locations of each tree and submitting these samples to the Clemson University Agricultural Services Laboratory for analysis.

Root density measurements were made by collecting two 5.77 cm (2.3 in.) diameter by 15.2 cm (6 in.) long soil cores from beneath each tree approximately 0.75 m (2.5 ft.) from the trunk. The samples were collected in early and late summer in opposing cardinal directions (i.e., North/South orientation in early summer; East/West in late summer). These cores were placed in wax-lined paper bags to prevent moisture loss and stored at 5°C (41°F) before processing.

Root density samples were washed through a 1 mm sieve to remove soil and retain fine roots. Root samples were further screened by hand to remove additional soil and organic matter and were stored in 50% ethanol at 5°C prior to measurement. Each root sample was scanned with WinRhizo 2003b software (Regent Systems, Quebec, Canada), and the resulting data were used to determine average root diameter (mm) and root length density (cm root/cm^3 soil). Once scanned, each sample was dried at 65°C for 3 days and weighed to determine root mass density (g dry root/cm^3 soil).

Approximately two grams of fine roots were retained from each core sample for vesicular-arbuscular mycorrhizal fungi (VAM) quantification. Roots were stored in 50% ethanol at 5°C prior analysis. Root samples were rinsed with distilled water, cleared with 10% KOH for 6-12 hours at 75°C, stained with trypan blue for 30 minutes at 75°C, and de-stained in 50% glycerol (Koske and Gemma, 1989). Root colonization was assessed using the magnified intersections method (McGonigle et al., 1990). For each sample, 3-4 30-40 cm root segments were mounted on a glass slide and examined under 100X magnification using a compound microscope equipped with a cross-hair eyepiece. The presence or absence of VAM hyphae was noted at 50 intersections between the eyepiece cross-hair and root segments. Colonization was then calculated as the percentage of hyphae present at these 50 intersections.

Pretreatment Tree Health

Tree size, condition and foliar nutrient content were assessed prior to treatment application (Table 4.2). Data from Pittsburgh, PA are incomplete, as foliage was not present at the time of pre-treatment evaluation.

Pittsburgh trees had larger mean trunk diameters than all other sites (15.9 ± 0.99 cm; 6.3 ± 0.38 in.), while trees in Anderson (11.8 ± 0.36 cm; 4.6 ± 0.14 in.) and Boston (12.7 ± 0.20 cm; 5.0 ± 0.08 in.) were larger in diameter than those in Myrtle Beach (6.17 ± 0.25 cm; 2.5 ± 0.10 in.). Visual condition ratings were highest in Anderson (7.04 ± 0.21), followed by Myrtle Beach (4.94 ± 0.27) and Boston (4.08 ± 0.07). Mean estimated chlorophyll densities were higher for trees in Anderson (37.1 ± 0.38) and Boston (37.9 ± 0.37) than those in Myrtle Beach (29.4 ± 0.92).

Table 4.2. Pre-treatment properties of red maple at four locations. Within-site means are followed by ±1 standard error. Means depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.05$).

Parameter	**N**	**Anderson**	**Boston**	**Myrtle Beach**	**Pittsburgh**[1]	***p*-value**
Foliar N (%)	50	1.55 ± 0.03^{b}	1.84 ± 0.03^{a}	$1.49 \pm .04^{b}$		.000
Foliar P (%)	50	0.09 ± 0.00^{c}	0.31 ± 0.01^{a}	0.23 ± 0.01^{b}		.000
Foliar K (%)	50	0.63 ± 0.03^{c}	0.92 ± 0.03^{a}	$0.74 \pm .03^{b}$		.000
Foliar Ca (%)	50	0.75 ± 0.02^{b}	0.72 ± 0.02^{b}	$1.61 \pm .07^{a}$		.000
Foliar Mg (%)	50	0.18 ± 0.01^{b}	0.24 ± 0.01^{a}	$0.26 \pm .01^{a}$		.000
Foliar Zn (ppm)	50	24.34 ± 0.93^{b}	28.74 ± 0.75^{b}	42.5 ± 2.68^{a}		.000
Foliar Cu (ppm)	50	8.98 ± 0.95	9.52 ± 0.30	9.36 ± 0.69		.856
Foliar Mn (ppm)	50	329.3 ± 30.27^{a}	143.76 ± 8.59^{b}	97.6 ± 16.04^{b}		.000
Foliar Fe (ppm)	50	106.12 ± 3.97^{c}	131.74 ± 4.33^{b}	159.2 ± 7.83^{a}		.000
Foliar S (%)	50	0.12 ± 0.00^{c}	0.13 ± 0.00^{b}	0.14 ± 0.00^{a}		.000
Foliar Na (ppm)	50	20.32 ± 0.57^{b}	29.22 ± 1.59^{b}	217.1 ± 28.7^{a}		.000
SPAD[2]	50	37.1 ± 0.38^{a}	37.9 ± 0.37^{a}	29.4 ± 0.92^{b}		.000
DBH (cm)[3]	50	11.8 ± 0.36^{b}	12.7 ± 0.20^{b}	6.17 ± 0.25^{c}	15.9 ± 0.99^{a}	.000
Condition[4]	50	7.04 ± 0.21^{a}	4.08 ± 0.07^{c}	4.94 ± 0.27^{b}		.000

[1] Data absent because foliage was not present at time of evaluation

[2] Mean foliar chlorophyll content measured with Minolta SPAD-502 (Minolta Inc, Japan)

[3] Stem diameter in inches measured with a diameter tape at approximately 4.5 feet from ground height

[4] Visual analysis based on a 1-10 scale assessing foliage color, crown density, dieback and vigor

Boston foliar tissue had higher initial levels of the macronutrients nitrogen, phosphorus and potassium. Myrtle Beach trees had the highest foliar levels of several nutrient cations: calcium, zinc, iron and sodium. Anderson foliage had lower levels of most nutrients, except for manganese.

Pretreatment Soil Data

Prior to treatment application, composite soil samples were collected from the upper 15 cm (6 in.) of soil beneath 6-8 trees at each site and analyzed by A&L Analytical Laboratory (Memphis, TN) to determine soil pH, CEC, organic matter content, and mineral nutrient concentrations (Table 4.3). Nutrient data from these samples were further analyzed with the Bartlett Tree Research Laboratories soil recommendations program to create a prescription fertilizer program to comply with ANSI A300 standards and adjust pH within the 5.0-6.0 range (Table 4.4). In general, Pittsburgh had higher soil nutrient levels than the other sites.

Experimental Design and Treatment Application

Five treatments, Airspade® tillage (A), fertilizer (F), mulch (M), Root Invigoration™ (AFM) and control (C), were applied to ten replicate trees at each site, for a total of 50 experimental units per site. In Boston, a completely randomized design was used. A randomized complete block design was used at the Anderson, Myrtle Beach and Pittsburgh sites to account for site variability. The treatments were applied in August 2005 in Boston, November 2005 in Anderson, November 2005 in Myrtle Beach and February 2006 in Pittsburgh.

All trees were treated with Roundup Pro herbicide (Monsanto Company, St. Louis, MO) in a 1.5 m (5 ft.) diameter circle around the trunk at least 14 days prior to treatment application to eliminate competing vegetation. Weed control was maintained throughout the experiment with additional Roundup applications as needed.

In Boston, an extensive turf root system remained after herbicide application, and it was necessary to remove the turf around trees receiving air tillage treatments (A and AFM) using a Ryan Jr. sod cutter (Jacobson, A Textron Company, Charlotte, NC). It is likely that some tree fine roots were damaged during this process.

Table 4.3. Chemical and physical properties of pre-treatment soil collected from each research site. Within-site means are followed by ± 1 standard error.

Parameter	**Anderson**[1]	**Boston**[2]	**Myrtle Beach**	**Pittsburgh**
ENR[3] (kg/ha)	85.5 ± 14.6	114	54.7 ± 9.5	74.4 ± 2.4
Soil P (ppm)	12.3 ± 2.6^{c}	288^{a}	38.3 ± 3.0^{c}	115.3 ± 20.2^{b}
Soil K (ppm)	138.7 ± 14.4^{b}	87^{c}	43.5 ± 7.4^{d}	276.7 ± 5.2^{a}
Soil Mg (ppm)	112.7 ± 23^{b}	99^{b}	64.3 ± 8.7^{b}	452.7 ± 27.9^{a}
Soil Ca (ppm)	942.3 ± 274.3b	977b	3648.5 ± 967.8^{ab}	5133.3 ± 768.4^{a}
Soil Na (ppm)	13.6 ± 0.3^{c}	39^{b}	30.3 ± 7.0^{ab}	85.3 ± 3.3^{a}
Sol. Salt (ppm)	0.3 ± 0	0.3	0.3 ± 0	0.2 ± 0.03
Soil Fe (ppm)	51.7 ± 3.7^{c}	295^{b}	134.5 ± 24^{c}	478.7 ± 31.9^{a}
Soil Mn (ppm)	104.3 ± 39.8^{b}	24^{b}	7.8 ± 1.4^{b}	312 ± 21.2^{a}
Soil Cu (ppm)	1.6 ± 0.3^{c}	9.6^{a}	0.6 ± 0.1^{c}	4.0 ± 0.5^{b}
Soil Zn (ppm)	2.7 ± 1.2^{b}	14.4^{a}	2.5 ± 0.5^{b}	5.2 ± 0.5^{b}
Soil OM (%)	2.8 ± 0.9	4.6	1.6 ± 0.4	2.0 ± 0.1
Soil CEC (meq/100g)	7.7 ± 1.1	9.6	19.0 ± 5.0	17.2 ± 1.8
Soil pH	5.7 ± 0.4	5.5	7.9 ± 0.1	6.8 ± 0.07
Bulk Density (g/cc)	1.41 ± 0.02b	1.14 ± 0.04d	1.74 ± 0.04a	1.25 ± 0.03c

[1] Chemical properties based on: Anderson n=3; Boston n=1; Myrtle Beach n=4; Pittsburgh n=3. Bulk density based on: n=50 at all sites.
[2] Post hoc analysis cannot be performed because *n*=1
[3] Estimated Nitrogen Release based on soil organic matter

Table 4.4. Fertilizer products applied to each AFM and fertilizer-treated soil area (7.1 m^2; 76.4 $ft.^2$).

Product	**Analysis**	**Manufacturer**	**Anderson (group #)**	**Boston**	**Myrtle Beach**	**Pittsburgh**
Boost Granular	24-7-7 S 6% Ca 1% Fe .10% Cu .05% Zn .05%	F.A. Bartlett Tree Expert Co. Stamford, CT	375 g (1) 470 g (2 & 3)	1.3 kg	565 g	262 g
Manganese Chelate	5% Mn 2% S	Growth Products LTD. White Plains, NY		79 ml	300 ml	
Tiger 90	0-0-0-90 S	Tiger-Sul Products Co Calgary, AB	565 g (1)		1.3 kg	
Epsom salt	100% $MgSO_4$	Top Co Associates LLC Skokie, IL	265 g (1)		455 g	169 g
Pelletized dolomitic lime	21% Ca 11% Mg	ASC Mineral Processing Allerton, IL	1.4 kg (2 & 3)			
Pelletized gypsum	20% Ca 16% S	ASC Mineral Processing Allerton, IL				3.5 kg
Disper-Sul plus Iron and Manganese	80% S 3.5% Fe 1.5% Mn	Martin Resources, Inc. Odessa, TX				1.1 kg

Trees receiving the M treatment were mulched to a depth of 5-7.5 cm (2-3 in.) in a 1.5 m (5 ft.) radius around the trunk using 0.45 m^3 (16 $ft.^3$) of bagged, shredded hardwood mulch. Trees receiving the F treatment were fertilized with the materials listed in Table 4.4; these were applied to the soil surface as a granular product or drench within the 1.5 m (5 ft.) radius. Trees receiving the A treatment were air-tilled to a depth of 15-20 cm (6-8 in.) using the Air Spade® series 2000 (Concept Engineering Group, Verona, PA) in a 1.5 m (5 ft.) radius around the trunk. Controls received no amendment or tillage treatment, but were maintained with a 1.5 m (5 ft.) radius vegetation-free zone.

The AFM treatment began with Airspade® tillage as described above. Soils were then amended with 0.28 m^3 (10 $ft.^3$) of bagged, composted cow manure and the prescription fertilizer used in the F treatment. Amendments were applied to the 1.5 m (5 ft.) radius and incorporated into the loosened soil profile with the Airspade®. Finally, amended soil received a mulch layer as described for the M treatment.

Immediately after treatment application, 30L (8 gal.) of irrigation was applied to the 1.5 m (5 ft.) radius of each tree at the Boston and Myrtle Beach sites. The Boston site received identical irrigation applications at one and three weeks post-treatment due to dry conditions.

Because of long-term seasonal drought in Anderson, water applications were required to prepare the soil for Airspade® treatments. At this site, all soils received 106 L (28 gals.) of water injected approximately 15 cm (6 in.) beneath the soil surface. Trees receiving the A and AFM treatments were given split applications: half of the water injected prior to treatment and half as a drench following treatment. Other treatments received the total water volume following treatment. In Pittsburgh, two inches of snow fell on the day after treatment application, obviating the need for post-treatment irrigation.

Water Relations

In June 2006 in Anderson, five Time Domain Reflectometry waveguides (Soilmoisture Equipment Corp., Santa Barbara, CA) were buried 15 cm (6 in.) below the soil surface. Two were placed under mulched soils and thee were placed under bare soils. Soil moisture content was collected weekly using the Trace System I (Soilmoisture Equipment Corp., Santa Barbara, CA). Pre-dawn leaf water potential was measured bi-weekly during the growing season using a 3005-series portable plant water status console (Soilmoisture Equipment Corp., Santa Barbara, CA).

Statistical Analyses

The effects of treatment, time, location and their interactions on response parameters were analyzed using a generalized linear model (SAS PROC GLIMMIX, SAS version 9.1; SAS Institute, Cary, NC). Root parameters did not meet normality and equality of variance assumptions, and ranks were therefore used in the model. All mean separations were performed with Fisher's least significant difference. Root parameters were evaluated at the $\alpha = 0.10$ significance level, due to the marked spatial variability of belowground data. All other parameters were tested at $\alpha = 0.05$.

Results

Tree Condition

Visual ratings on a 0-10 scale were assigned by trained arborists and were based on crown density, leaf color and vigor (Fig. 4.1). Across all sites, average visual condition ratings for AFM-treated trees were significantly higher than those of control trees at the end of the second growing season ($p = 0.0268$; Fig. 4.2). At Myrtle Beach, fertilized trees also had higher condition ratings than controls ($p = 0.0176$; data not shown).

Tree Growth

DBH showed a greater increase in AFM-treated trees than in control trees at two out of four sites: Myrtle Beach and Pittsburgh ($p < 0.05$; Fig. 4.3). Compared to controls, AFM trees in Myrtle Beach and Pittsburgh showed a 126% and 64% greater increase in DBH, respectively. In Pittsburgh, Airspade®-treated trees also showed a greater increase in DBH than controls. In Myrtle Beach, AFM and fertilized trees exhibited greater twig elongation than Airspade®-treated trees ($p<0.01$; Fig. 4.4).

Chlorophyll and Foliar Nutrients

Across all sites, AFM-treated trees had higher leaf chlorophyll content than Airspade®- and mulch-treated trees in fall 2006 ($p < 0.05$; Fig. 4.5). A similar result was not seen in the second growing season.

Across all sites and years, no treatment - individual or combined - differed in foliar nutrient concentration from control. Across all sampling dates and locations, AFM

Figure 4.1. Examples of tree condition ratings. Based on trained arborist inspections, the tree on the left received a condition rating of 4, while the tree on the right was rated a 10.

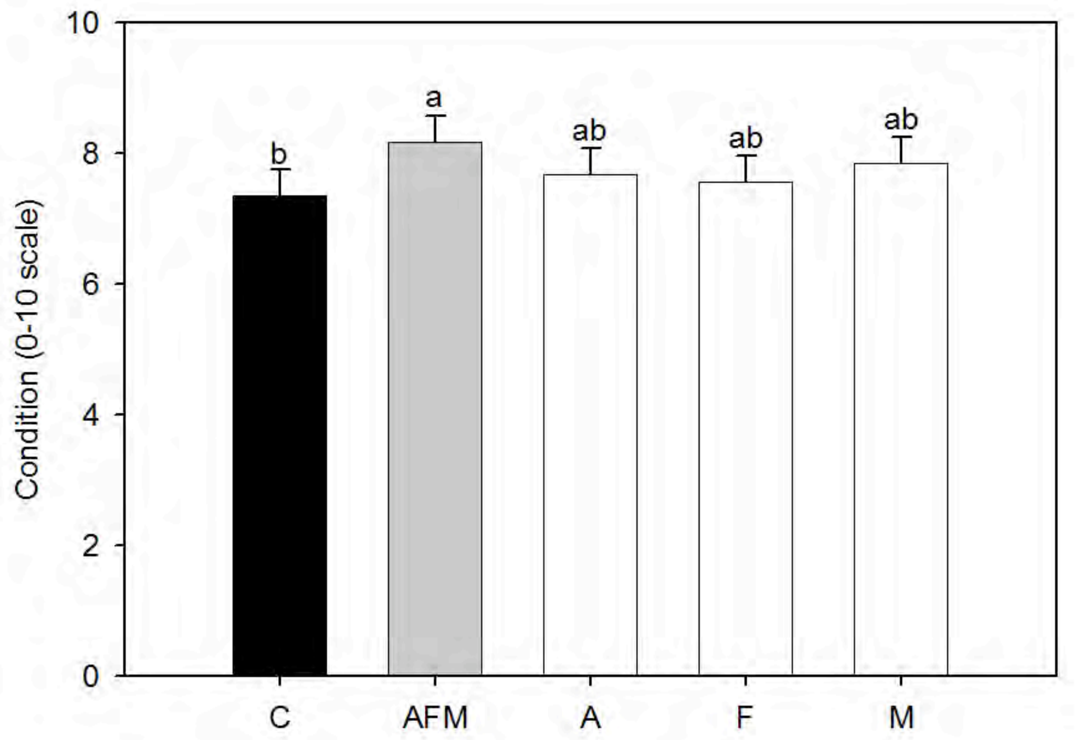

Figure 4.2. Visual condition ratings in fall 2007. Data are pooled from all sites. Error bars represent one standard error of the mean. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.05$).

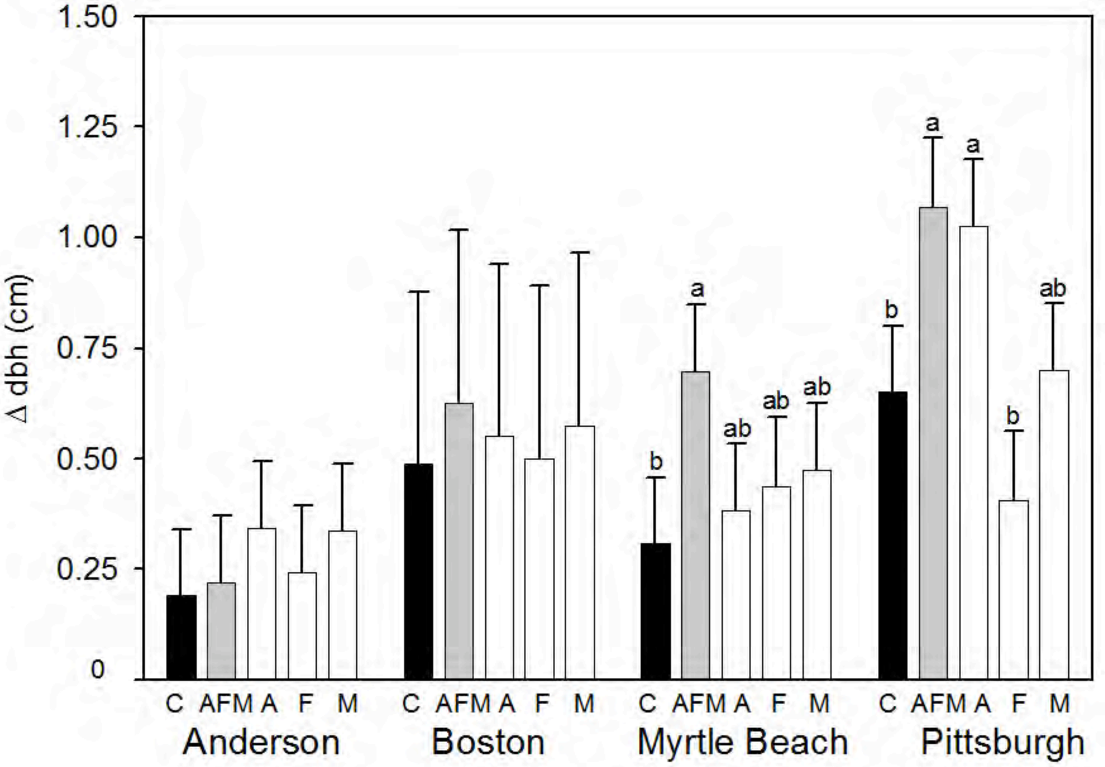

Figure 4.3. Mean change in dbh during 2007 growing season (n=10 per treatment group). Error bars represent one standard error of the mean. Treatment means within a site depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.05$).

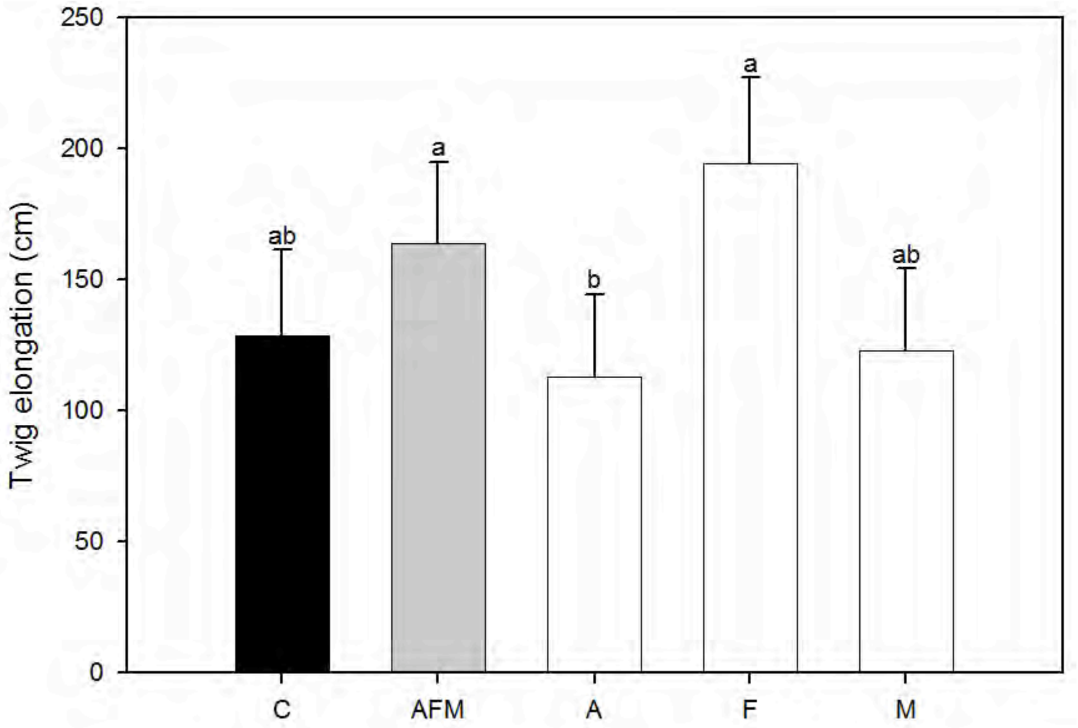

Figure 4.4. Mean twig elongation during the 2007 growing season in Myrtle Beach (n=10 per treatment group). Error bars represent one standard error of the mean. Treatment means within a site depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.05$).

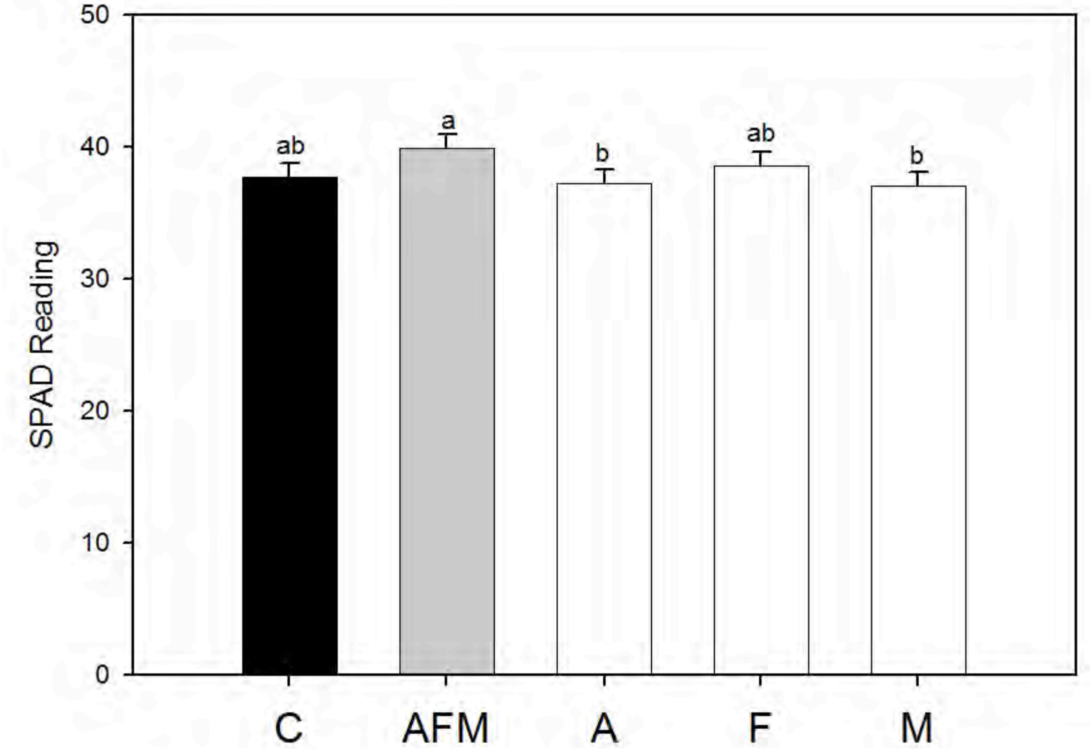

Figure 4.5. Foliar chlorophyll density in fall 2006 estimated with SPAD meter. Data from all sites been pooled (n=40 per treatment group). Error bars represent one standard error of the mean. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure (α = 0.05).

trees had higher levels of foliar potassium than fertilized trees, although they did not significantly differ from controls ($p = 0.035$; Fig. 4.6). At no time were levels of foliar nutrients considered deficient based on sufficiency levels for *Acer rubrum* (Mills and Jones, 1996; Tables 4.5, 4.6, 4.7 and 4.8).

There were some differences in individual nutrients on specific dates and sites. Across all sites in fall 2006, AFM, A and M trees had higher levels of foliar phosphorus than trees receiving the F treatment ($p < 0.05$; Fig. 4.7). In Pittsburgh, AFM-treated trees had higher levels of foliar potassium than all other treatments, and fertilizer-treated trees had the lowest potassium levels (Table 4.8). Also in Pittsburgh, the mulch treatment reduced foliar magnesium and zinc, while Airspade® tillage reduced foliar calcium and zinc.

In Myrtle Beach, foliar phosphorus, magnesium and zinc were increased with AFM relative to control (Table 4.7). Fertilizer increased foliar zinc and magnesium, while mulch increased foliar zinc and phosphorus relative to control.

Water Relations

Water relations were measured at the Anderson, SC site only. Although there were no differences in pre-dawn leaf water potential between mulched and unmulched trees in 2006, differences did emerge during the extreme drought of 2007. M-treated trees had higher pre-dawn water potentials than control trees in July 2007 (Fig. 4.8), and both AFM and M trees exhibited higher pre-dawn water potentials than controls in August 2007. Airspade® and fertilizer-treated trees never differed from control in leaf water potential.

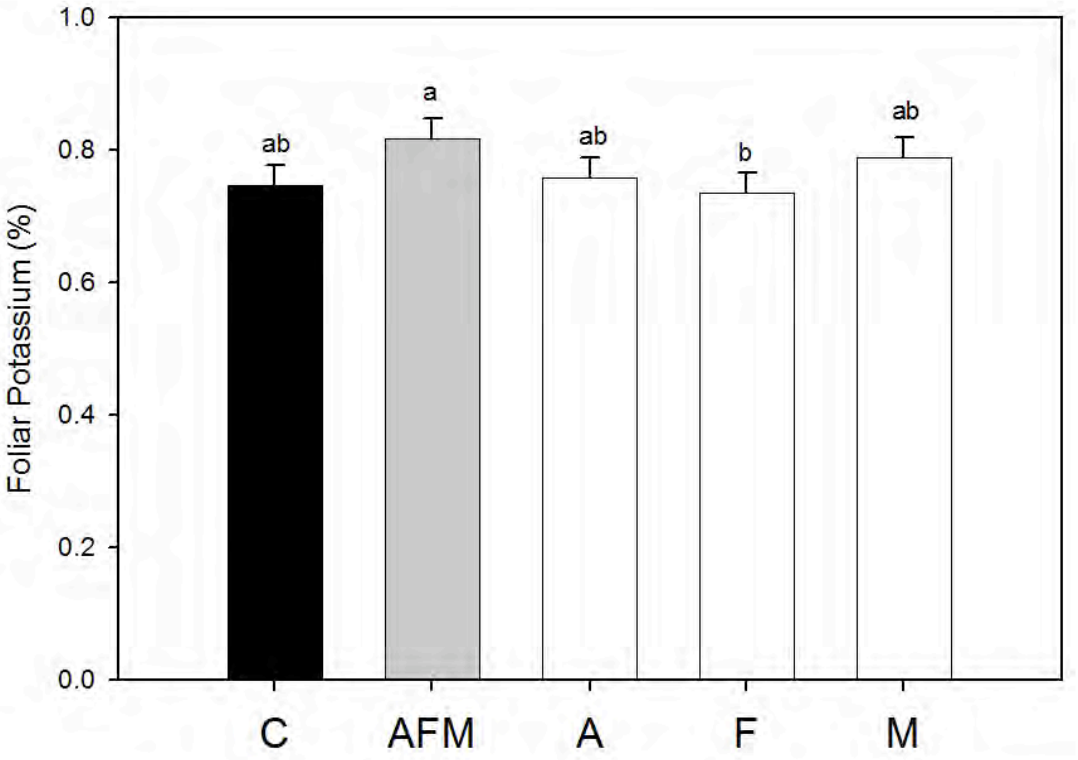

Figure 4.6. Foliar potassium levels pooled from all sites and sampling dates (n=160 per treatment group). Error bars represent one standard error of the mean. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.05$).

Table 4.5. Treatment means across all post-treatment sampling dates in Anderson. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.05$).

Parameter	Airspade®	Control	Fertilizer	Mulch	AFM	SE[1]
Foliar N (%)	1.81	1.76	1.76	1.76	1.77	0.07
Foliar P (%)	0.12	0.12	0.12	0.12	0.13	0.02
Foliar K (%)	0.71^{ab}	0.72^{ab}	0.69^{b}	0.74^{ab}	0.79^{a}	0.04
Foliar Ca (%)	0.57	0.55	0.59	0.59	0.60	0.07
Foliar Mg (%)	0.18	0.18	0.19	0.19	0.20	0.02
Foliar Zn (ppm)	21.0	18.8	19.0	20.8	20.4	2.9
Foliar Cu (ppm)	9.0	8.8	8.5	7.8	8.5	1.2
Foliar Mn (ppm)	251.2	244.0	235.4	269.5	280.5	78.5
Foliar Fe (ppm)	84.7	88.7	78.2	84.7	82.7	10.0
Foliar S (%)	0.12	0.12	0.12	0.12	0.12	0.01
Foliar Na (ppm)	12.7	13.1	12.5	13.8	13.6	34.9
SPAD	38.0	38.1	38.0	38.6	37.9	1.1
Condition	7.68	7.95	7.85	7.85	8.12	0.4
RLD (cm/cc)	7.5^{ab}	5.4^{c}	6.4^{bc}	6.7^{ab}	7.6^{a}	0.8
RMD (g/cc)	4.0^{a}	3.1^{b}	4.1^{a}	4.1^{a}	3.8^{ab}	0.7
Root dia.(mm)	0.45^{bc}	0.69^{a}	0.70^{a}	0.68^{ab}	0.64^{c}	0.02
SRL (m/g)	20.3^{ab}	18.6^{bc}	16.4^{c}	17.6^{c}	20.7^{a}	2.2

[1] Standard error pooled across all sampling dates (SAS PROC GLIMMIX)

Table 4.6. Treatment means across all post-treatment sampling dates in Boston. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure (α = 0.05).

Parameter	**Airspade®**	**Control**	**Fertilizer**	**Mulch**	**AFM**	**SE[1]**
Foliar N (%)	1.84	1.73	1.86	1.81	1.84	0.2
Foliar P (%)	0.25	0.22	0.22	0.25	0.22	0.04
Foliar K (%)	0.78	0.74	0.77	0.76	0.76	0.1
Foliar Ca (%)	0.46	0.47	0.48	0.51	0.48	0.2
Foliar Mg (%)	0.18	0.18	0.17	0.18	0.18	0.05
Foliar Zn (ppm)	26.9	26.7	27.4	27.8	26.9	9.0
Foliar Cu (ppm)	6.5	6.3	6.4	6.3	5.9	3.6
Foliar Mn (ppm)	113.6	140.4	111.3	125.4	111.4	245.0
Foliar Fe (ppm)	71.1	71.5	64.3	69.6	64.8	29.0
Foliar S (%)	0.12	0.11	0.12	0.12	0.12	0.02
Foliar Na (ppm)	26.1	30.8	25.3	22.4	22.8	106.6
SPAD	41.1	40.2	42.2	40.8	41.8	3.3
Condition	7.85	7.60	7.73	7.88	8.03	1.3
RLD (cm/cc)	6.8	8.0	6.5	7.0	5.6	2.0
RMD (g/cc)	3.4	3.5	3.6	3.3	3.0	1.9
Root dia. (mm)	0.69^{b}	0.70^{ab}	0.72^{a}	0.66^{c}	0.70^{b}	0.02
SRL (m/g)	20.6	19.6	17.7	21.9	18.9	5.9

[1] Standard error pooled across all sampling dates (SAS PROC GLIMMIX)

Table 4.7. Treatment means across all post-treatment sampling dates in Myrtle Beach. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure (α = 0.05).

Parameter	**Airspade®**	**Control**	**Fertilizer**	**Mulch**	**AFM**	**SE[1]**
Foliar N (%)	1.70	1.69	1.82	1.71	1.75	0.07
Foliar P (%)	0.21^{ab}	0.18^{b}	0.18^{b}	0.23^{a}	0.23^{a}	0.02
Foliar K (%)	0.73	0.74	0.73	0.78	0.81	0.04
Foliar Ca (%)	1.05	0.95	1.03	1.00	0.93	0.07
Foliar Mg (%)	0.21^{ab}	0.18^{b}	0.21^{a}	0.21^{ab}	0.22^{a}	0.02
Foliar Zn (ppm)	33.1^{ab}	27.2^{b}	34.0^{a}	34.4^{a}	36.9^{a}	3.0
Foliar Cu (ppm)	10.0	9.2	8.5	8.8	10.0	1.2
Foliar Mn (ppm)	66.4	64.1	90.1	55.9	225.3	78.6
Foliar Fe (ppm)	122.1^{ab}	122.6^{ab}	138.1^{a}	113.3^{b}	119.4^{ab}	10.0
Foliar S (%)	0.14	0.13	0.15	0.13	0.14	0.01
Foliar Na (ppm)	219.2^{ab}	241.5^{a}	229.8^{a}	154.9^{b}	190.9^{ab}	34.9
SPAD	32.2	32.2	34.1	32.1	34.5	1.1
Condition	6.15^{b}	6.13^{b}	7.03^{a}	6.93^{ab}	7.10^{a}	0.4
RLD (cm/cc)	3.6^{b}	4.2^{ab}	5.5^{a}	5.0^{a}	5.4^{a}	0.8
RMD (g/cc)	1.8^{b}	2.2^{ab}	2.6^{a}	2.6^{a}	2.3^{ab}	0.7
root dia. (mm)	0.62	0.59	0.62	0.62	0.58	0.02
SRL (m/g)	25.5^{ab}	28.9^{b}	23.6^{ab}	23.6^{b}	27.1^{a}	2.2

[1] Standard error pooled across all sampling dates (SAS PROC GLIMMIX)

Table 4.8. Treatment means across all post-treatment sampling dates in Pittsburgh. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure (α = 0.05).

Parameter	**Airspade®**	**Control**	**Fertilizer**	**Mulch**	**AFM**	**SE[1]**
Foliar N (%)	1.80^{b}	1.89^{ab}	1.92^{ab}	1.96^{a}	1.96^{a}	0.07
Foliar P (%)	0.33^{a}	0.32^{ab}	0.28^{b}	0.31^{ab}	0.29^{ab}	0.02
Foliar K (%)	0.81^{abc}	0.78^{bc}	0.75^{c}	0.87^{ab}	0.90^{a}	0.04
Foliar Ca (%)	0.87^{b}	1.03^{a}	0.98^{ab}	0.88^{ab}	0.90^{ab}	0.07
Foliar Mg (%)	0.24^{ab}	0.27^{a}	0.25^{ab}	0.22^{b}	0.25^{ab}	0.02
Foliar Zn (ppm)	32.5^{b}	40.5^{a}	36.8^{ab}	33.3^{b}	33.6^{ab}	3.0
Foliar Cu (ppm)	9.7	11.3	9.6	9.8	10.9	1.2
Foliar Mn (ppm)	370.7	541.1	351.6	381.4	484.9	78.6
Foliar Fe (ppm)	88.6	96.7	92.9	85.2	96.2	10.0
Foliar S (%)	0.14^{b}	0.15^{ab}	0.16^{a}	0.13^{b}	0.14^{ab}	0.01
Foliar Na (ppm)	30.6	33.2	40.2	21.9	41.1	34.9
SPAD	38.1	38.7	38.3	39.1	40.0	1.1
Condition	8.35^{ab}	8.05^{ab}	7.70^{b}	8.20^{ab}	8.85^{a}	0.4
RLD (cm/cc)	6.1^{c}	9.7^{a}	8.5^{ab}	7.4^{bc}	6.0^{bc}	0.8
RMD (g/cc)	4.0^{ab}	5.5^{a}	4.7^{a}	5.5^{b}	3.9^{b}	0.7
root dia. (mm)	0.74^{a}	0.69^{c}	0.75^{a}	0.74^{ab}	0.72^{b}	0.02
SRL (m/g)	16.4^{b}	20.8^{a}	19.3^{ab}	18.2^{ab}	18.0^{ab}	2.3

[1] Standard error pooled across all sampling dates (SAS PROC GLIMMIX)

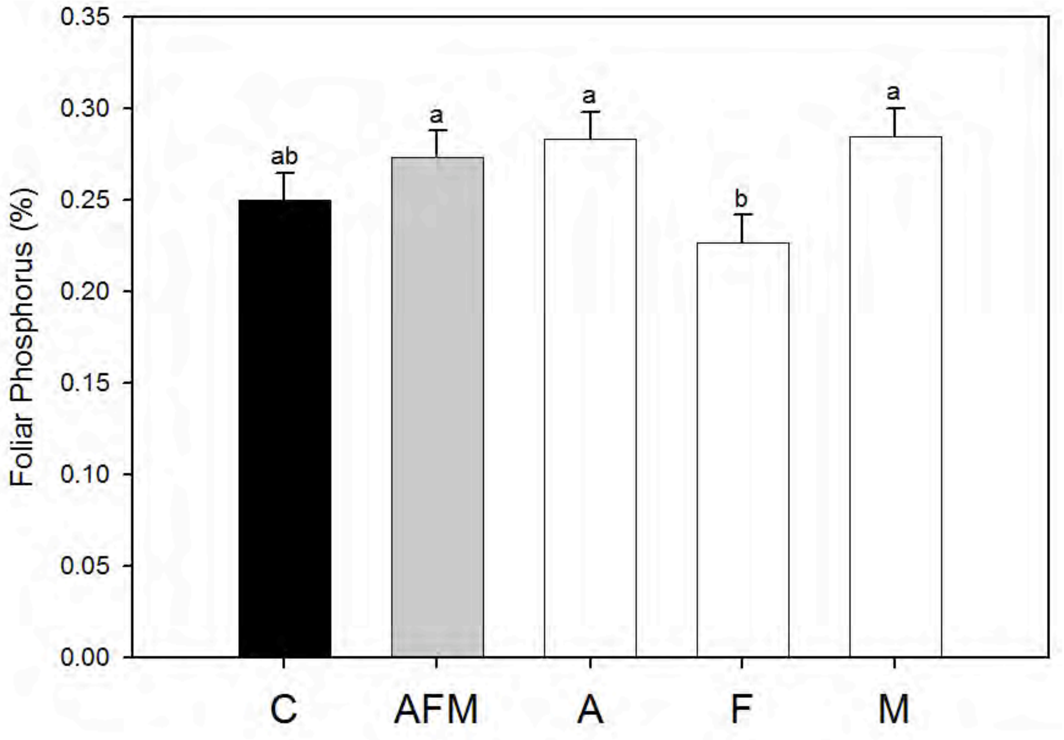

Figure 4.7. Foliar phosphorus levels in fall 2006 (n=40 per treatment group). Data from all sites have been combined Error bars represent one standard error of the mean. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.05$).

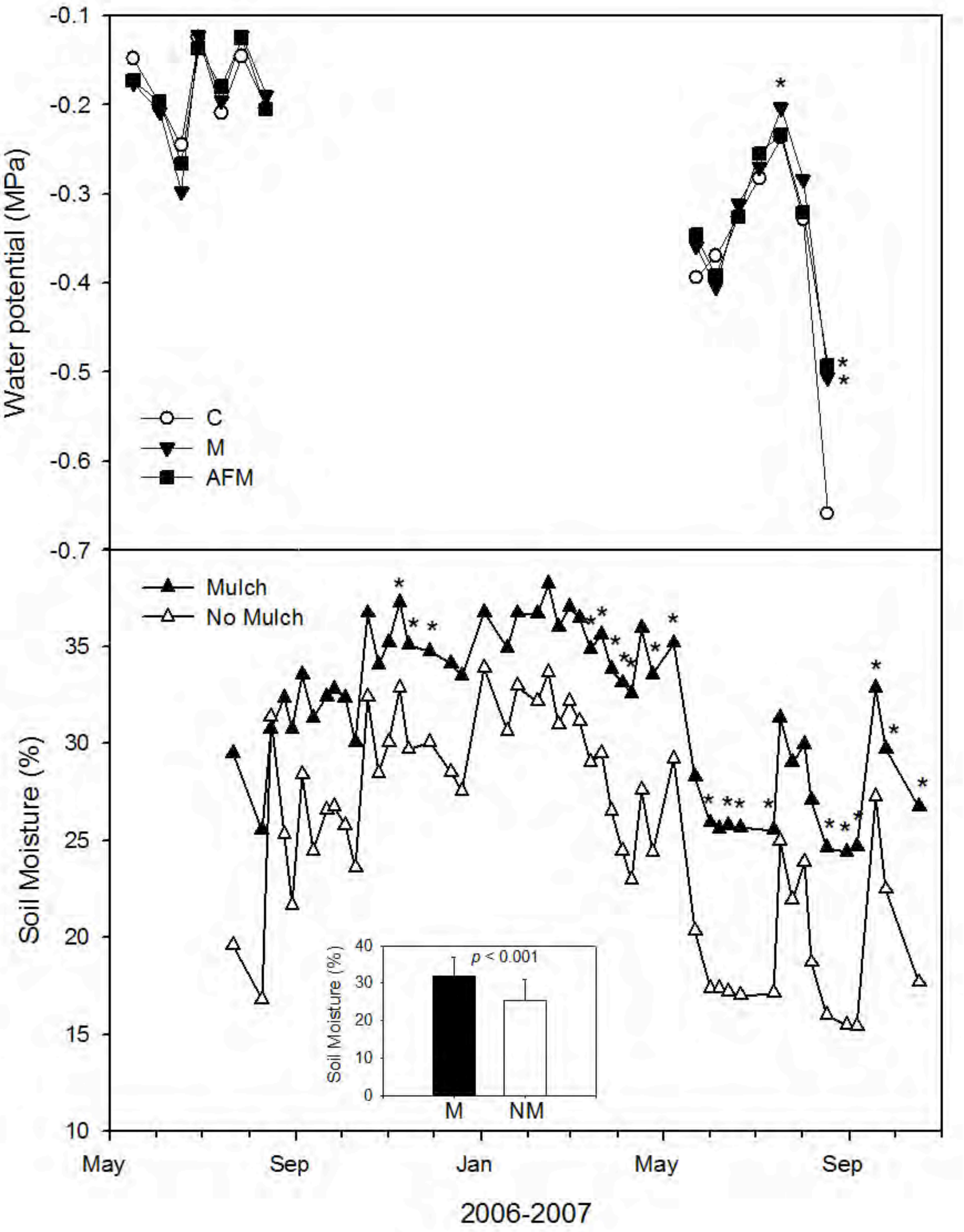

Figure 4.8. Pre-dawn water potential and percent soil moisture throughout 2006 and 2007 seasons in Anderson (soil moisture: n=2 for mulch and n=3 for no mulch; water potential: n=10 per treatment group). Inset panel shows overall means for two seasons. *Denotes a significant difference in treatment means at α=0.05 using Fisher's multiple comparisons procedure. Fall coloration of foliage in Anderson began in mid-September with leaf drop commencing in mid-October.

Root Growth

In spring 2006, root length density (RLD) and root mass density (RMD) for AFM-treated trees were lower than control, fertilizer and mulch trees across all sites ($p < 0.10$; Fig. 4.9; Fig. 4.10). However, by fall 2006, AFM-treated trees had higher mean RLDs than controls ($p = 0.0821$). Specific root length (i.e. the length of one gram of root tissue) was highest in AFM-treated trees in fall 2006 ($p < 0.10$; Fig. 4.11). RMD did not differ among treatments after spring 2006. Neither RLD nor SRL differed among treatments after fall 2006.

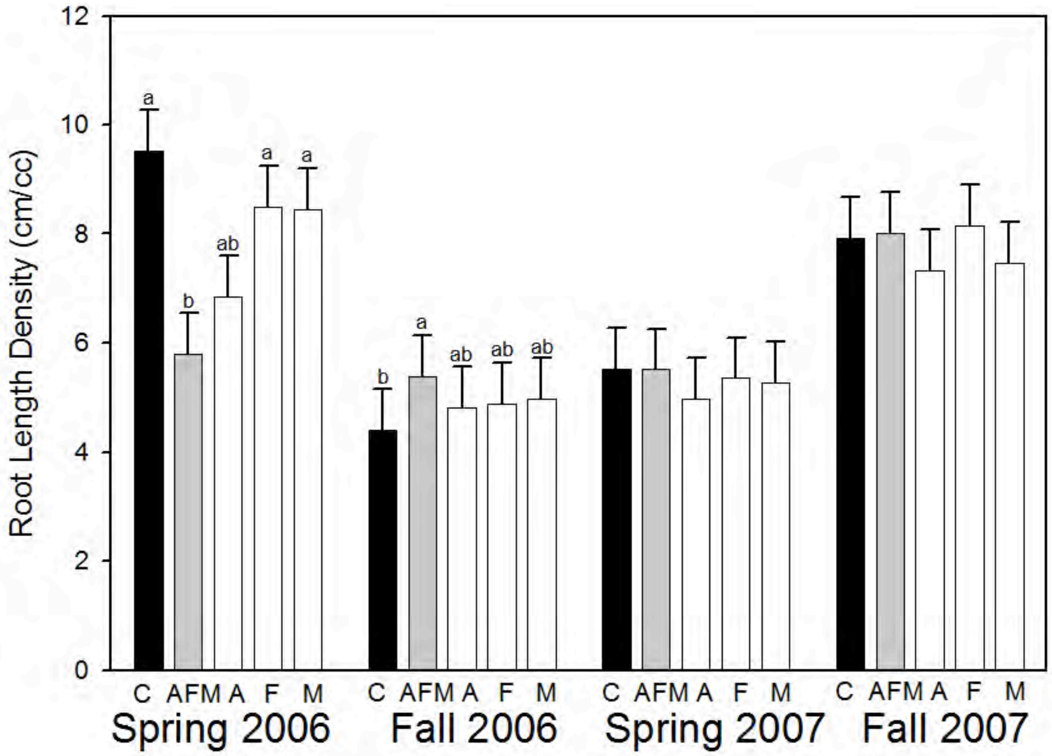

Figure 4.9. Root length density over time. Data from all sites have been combined (n=40 per treatment group). Error bars represent one standard error of the mean. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.10$).

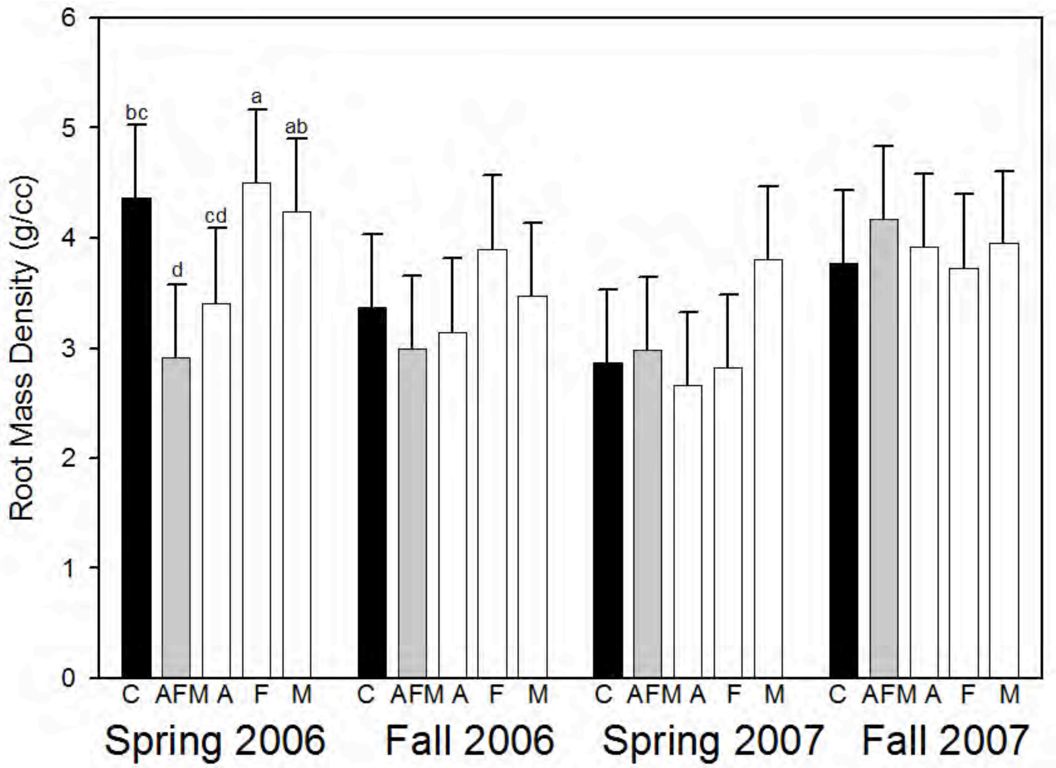

Figure 4.10. Root mass density over time. Data from all sites have been combined (n=40 per treatment group). Error bars represent one standard error of the mean. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.10$).

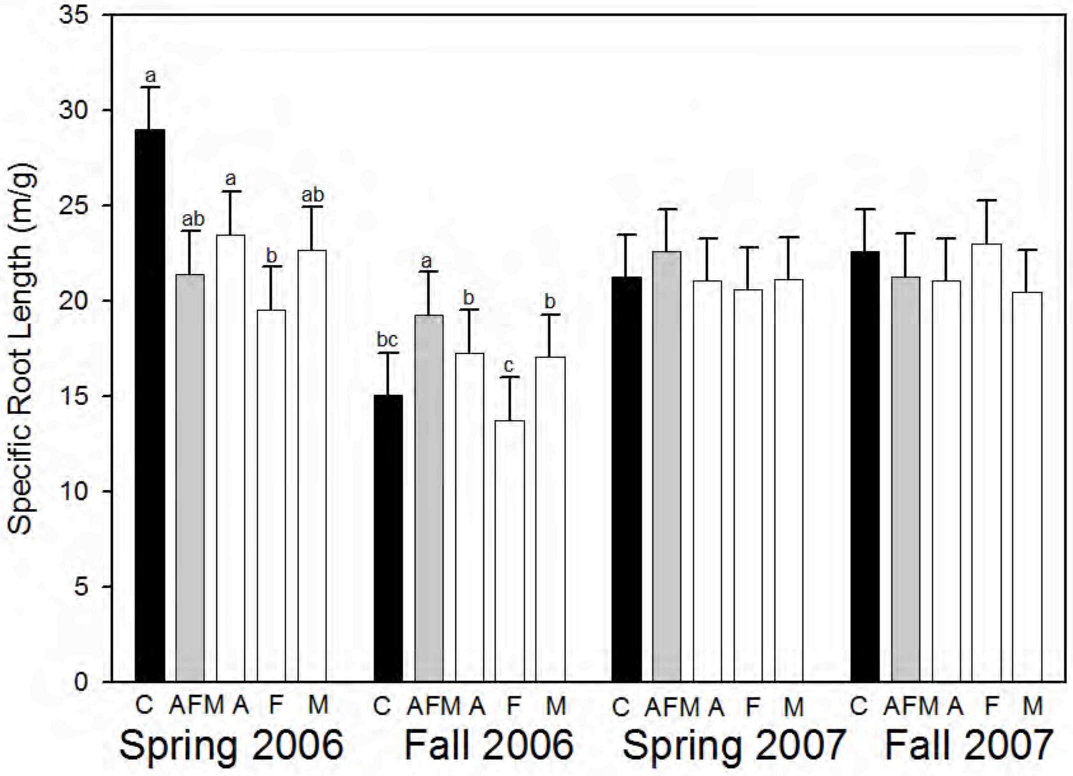

Figure 4.11. Specific root length over time. Data from all sites have been combined (n=40 per treatment group). Error bars represent one standard error of the mean. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.10$).

Across all sites, mean fine root diameter was consistently greater in fertilized trees compared to other treatments (Fig. 4.12). Fertilizer-treated trees also had lower SRLs than Airspade®, mulch and AFM trees. There were no differences among treatments in the degree of VAM colonization. The average percent colonization was 13.4% across all sites and years. Averaged across both years, percent colonization was 9.5%, 10.9%, 15.6% and 18.2% at Anderson, Myrtle Beach, Boston and Pittsburgh, respectively, none of which were significantly different from one another.

Discussion

Responses of red maples to Root Invigoration™ (AFM treatment) and its three individual components were evaluated at four urban sites. The AFM treatment improved tree growth and condition to a greater extent than any individual component, although water relations were improved as much by mulch as by the full AFM treatment. Specific tree responses are discussed in detail below.

Tree Condition

Two growing seasons after treatment application, visual condition ratings for AFM trees were significantly higher than controls. No other treatment produced this improvement. Watson et al. (1996) noted improvements in the appearance of white oak when using soil replacement techniques in the rooting zone. Native soil was replaced with 100% leaf compost or a 50% compost/50% native soil mix in trenches beneath white oaks. No canopy data were presented, but tree visual appearance was reported to have

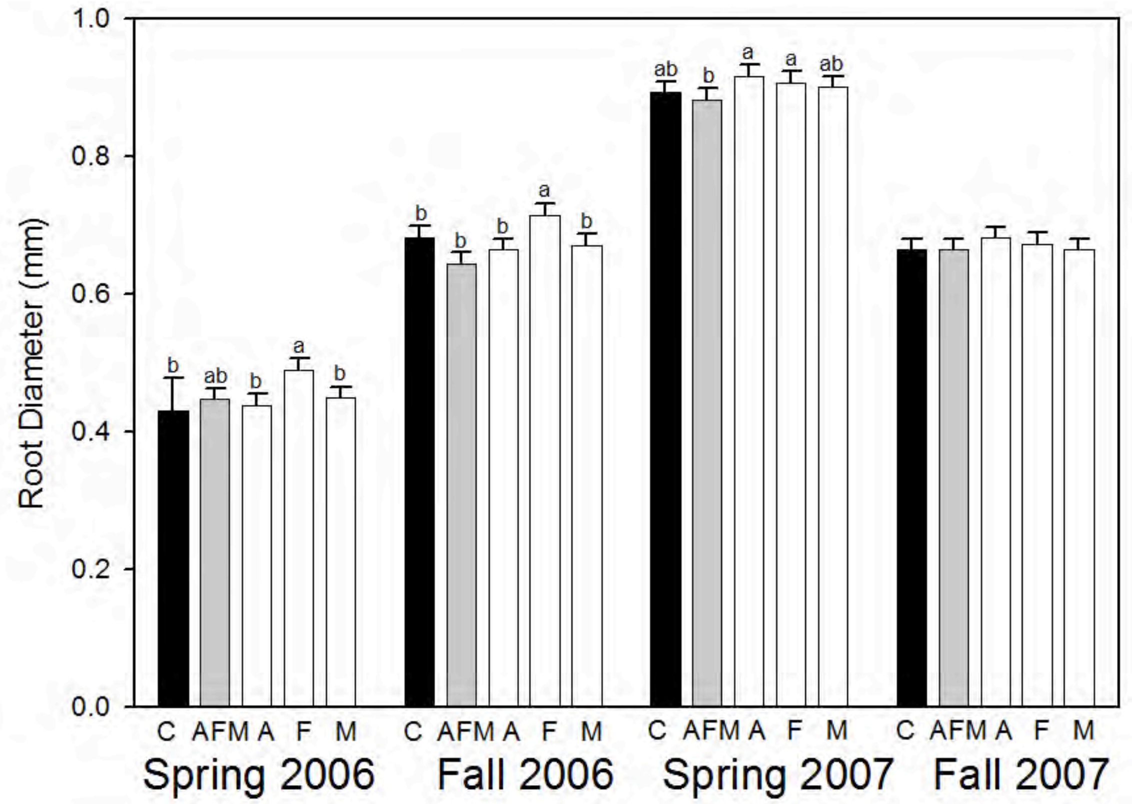

Figure 4.12. Mean root diameter over time. Data from all sites have been combined (n=40 per treatment group). Error bars represent one standard error of the mean. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.10$).

improved following treatment. Canopy appearance was improved with AFM, while individual treatments did not improve appearance relative to control.

Tree Growth

At several sites, AFM promoted increased diameter growth and twig elongation. Previous methods for improving the soil environment of established shade trees have yielded mixed results (Hascher and Wells, 2007; Rolf, 1992; Smiley, 2001; Watson et al., 1996). In studies designed to test the benefits of soil fracturing equipment, neither root growth stimulation nor tree growth enhancement have been observed (Hascher and

Wells, 2007; Rolf, 1992; Smiley, 2001). However, programs that both reduced mechanical impedance to root growth and incorporated soil amendments produced growth enhancement in callery pear and white oak (Day and Bassuk, 1994; Watson et al., 1996).

In the current study, individual treatments such as mulching or fertilizer generally provided no growth benefit relative to control. AFM in Myrtle Beach and A and AFM treatments in Pittsburgh significantly increased DBH relative to control, while F and AFM in Myrtle Beach were associated with greater twig elongation. However, Freadrich and Ham (1982) noted greater diameter growth in mulched silver maple and increased shoot growth in mulched silver, red and sugar maples. After two growing seasons, these growth benefits from mulch alone were not observed. AFM repeatedly provided more growth during this study.

Chlorophyll and Foliar Nutrients

There were few differences in foliar chlorophyll concentrations and nutrient levels among treatments. It is worth highlighting that foliar phosphorus levels in fall 2006 were lower for fertilized trees than for AFM, Airspade® and mulch-treated trees. Across all sites and sampling dates, foliar potassium levels were also lower for fertilized trees than for AFM trees. These results suggest that simply fertilizing poor soils will not significantly improve tree health and may even be counterproductive. On poor sites, improvements in soil physical properties may be required to fully realize the benefits of fertilizer applications.

The general lack of response to fertilizer may also reflect adequate tree nutrition prior to treatment application (Table 4.2). At no time, pre or post-treatment, were foliar nutrient levels deficient. Furthermore, nutrients taken up by larger AFM trees may have been diluted within a denser, more extensive canopy (Marschner, 2002).

Water Relations

A mulch layer as the M treatment or as part of AFM, increased soil moisture beneath mulched trees (Fite et al., 2008). This increase was associated with reduced tree water stress during the 2007 drought. During August 2007, upstate South Carolina was experiencing a 30 cm (11.8 in.) annual precipitation deficit and was considered to be under extreme drought by the National Weather Service Palmer Drought Severity Index (Service, 2007). On July 17, 2007, mulched trees had 16% higher water potentials than controls. On August 18, 2007, M and AFM trees had 30% and 33% higher water potentials than controls, respectively. Increased soil moisture levels due to a mulch layer lead to reduced tree water stress.

Root Responses

In spring 2006, RLD (cm root/cm^3 soil) and RMD (g root/cm^3 soil) were reduced by the AFM treatment. Although not significant, RLD and RMD of Airspade® trees also trended lower, suggesting that air-tillage could be responsible for a transient decline in fine root length. By fall 2006, mean RLD of AFM trees was higher than controls, while that of "A" trees was similar to controls. This result is in agreement with Watson et al. (1996), who suggest that damage to fine roots from brief exposure to air is overcome in a single season. Longer, thinner roots (high SRL) were also characteristic of AFM trees at the end of 2006, an effect that did not persist into the second year.

Treatment differences in fine root density and morphology had effectively disappeared by the second year of the study, suggesting that these differences were more strongly related to the perturbations of treatment application than to the resulting changes in soil conditions. While studies on localized nutrient addition often report greater fine root production in the fertilized/amended area (Eissenstat and Caldwell, 1988; Hodge et al., 2000; Watson, 2002; Watson et al., 1996), overall increases in soil fertility more commonly have no effect on or reduce fine root growth (Eissenstat and Caldwell, 1988; May et al., 1965; Philipson and Coutts, 1977; Watson, 1994). Neither response was observed in this study, and continued data collection at the sites will help to determine whether changes in fine root production emerge over longer timescales.

Conclusion

Individual components of the Root Invigoration™ process rarely provided similar benefits to the combined program. Collectively, these treatments are more beneficial. Arborists should evaluate the tree, site, and budget to determine how best to achieve client goals. In some cases, goals may be met by an individual treatment (i.e. plant water potential benefits of mulch alone). However, a more holistic approach like RI may provide significantly greater benefits.

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CHAPTER V

ROOT RESPONSE

Introduction

The benefits provided by urban trees are increasingly recognized but rarely achieved due, in part, to stresses imposed by urban soils. While forest soils have a well-developed humus layer, urban soils typically lack an upper organic horizon (Fraedrich and Ham, 1982). Urban soils also tend to be highly compacted, with bulk densities higher than those of similar soils in nearby forested areas (Close et al., 1996a). Low porosity, poor aeration, and increased moisture fluctuations in compacted soil lead to poor growth and high mortality rates in urban trees (Watson et al., 1996). The Root Invigoration™ (AFM) process, developed by the F.A. Bartlett Tree Expert Co., is designed to improve conditions for fine root growth by incorporating organic matter and fertilizer into the rooting zone while simultaneously reducing soil compaction and increasing aeration.

To relieve soil compaction, soil is loosened to a depth of 15-20 cm (6-8 in.) using an Air Spade® (Concept Engineering Group, Verona, PA), a tool that channels compressed air through a specialized tip. The treated soil is amended with composted organic matter and fertilizer products based on prior soil analyses. These amendments are blended into the existing soil with the AirSpade®. Finally, the treated area is mulched to a depth of 5-7.5 cm (2-3 in.) to help retain soil moisture. Irrigation is applied following treatment to settle the soil and counteract the drying effects of the AirSpade® tillage.

Ongoing research in our lab involves measuring the root responses of red maple (*Acer rubrum*) to Root Invigoration™ at four urban locations: Anderson, SC; Boston, MA; Myrtle Beach, SC and Pittsburgh, PA. Additional treatments include control, AirSpade® tillage only, mulching only and fertilization only.

Treatment of soils with the AFM program or mulch alone led to significant increases in soil organic matter content (Fite et al., 2008). Soil concentrations of phosphorus, potassium, magnesium, manganese, boron and zinc were increased in AFM-treated soils (Fite et al., 2008). Mulched soils (i.e. mulch only or the AFM program) had higher levels of soil moisture than bare soils (Fite et al., 2008).

AFM treatment reduced soil strength in the two years following treatment application (Fite et al., 2008). Soils treated with Airspade® tillage alone and mulch alone reduced soil strength the first season, but by the second season, the soil strength for these treatments was no different than control (Fite et al., 2008). The improvements in the soil environment created by AFM have lead to improved crown condition, increased diameter growth, elevated foliar levels of phosphorus and potassium (Fite et al., 2009).

Although soil cores showed few differences in root length density among treatments, (Fite et al., 2009), coring data do not accurately measure root production, and mortality (Hendrick and Pregitzer, 1992). The cores collected from the root zones of the trees only reflect a static measure of what roots are present at a single point in time and fail to capture root dynamics. Of the few differences, AFM root length and mass densities were reduced initially, but had recovered by the end of the first season (Fite et al., 2009). This initial reduction could be the result of physical damage or drying of the root system, or of an enhanced soil environment.

Roots rapidly respond to their environment, and may do so with as much, if not more, variability as observed in shoots (Pregitzer, 2003). The flexibility in carbon resource allocation allows root systems to exploit areas of soil volume that are more favorable for nutrient and water uptake (Eissenstat, 1992; Hodge, 2004). These areas of opportunity often result from organic inputs and their subsequent decomposition (Hodge, 2004). However, many questions remain about root activity due to the inherent inaccessibility of root systems, and these questions cannot be accurately answered by destructive techniques.

Minirhizotrons (root observation tubes) are often employed as a nondestructive method of observing root production and disappearance (Johnson et al., 2001). Minirhizotrons consist of plastic tubes installed in the ground which allow specially-adapted camera systems to capture images of fine roots that have grown against the outer surface of the tube (Johnson et al., 2001). They allow for direct observation of individual roots and provide estimates of root turnover that cannot be obtained from traditional core sampling methods (Hendrick and Pregitzer, 1992). They provide a means to document fine root characteristics including production, growth, mortality, phenology and lifespan (Johnson et al., 2001).

We used minirhizotron data from approximately 10-yr-old red maple to evaluate the response of fine roots to the imposed treatments. Root length, production, mortality, depth and diameter were assessed and treatment effects were compared to controls. The

Cox proportional hazards regression technique was also used to analyze the effects of these treatments on root longevity.

Here we focus on results obtained at the Anderson site where minirhizotrons have been installed beneath all treated trees.

Materials and Methods

Experimental Site

Three groups of trees at the Anderson Sports and Entertainment Center (ASEC) in Anderson, SC, were selected for use in this study. The first group included 30 red maples located along the sidewalks leading to the civic center; these trees had an average trunk diameter of 12.7 cm (5 in.) at 1.4 m (4.5 ft) above the soil line (dbh). At the time of treatment application, they displayed little internode elongation and thin, chlorotic canopies. The soil in this group was a sandy loam with 60%, 22% and 18% sand, silt and clay, respectively. The second group was located in an open field within the ASEC and included five recently-planted red maples with thin, chlorotic canopies, moderate limb dieback, and an average dbh of 7.6 cm (3 in.). The soil in this group was a sandy clay with 46%, 18% and 36% sand, silt and clay, respectively. The third group of trees included 15 red maples planted near a sports field with an average dbh of 10.2 cm (4 in.). These trees had relatively healthy canopies, with very little chlorosis or dieback. The soil in this group was a sandy clay loam with 58%, 18% and 24% sand, silt and clay, respectively.

Pre-treatment foliage samples were also collected in September 2005 and analyzed for nutrient concentrations by the Clemson University Agricultural Services Laboratory. A pre-treatment summary of tree parameters is given in Table 5.1.

Pre-treatment soil samples were collected in October 2005 and analyzed by A&L Analytical Laboratory (Memphis, TN) to determine soil pH, CEC, organic matter content, and mineral nutrient concentrations (Table 5.2). One approximately 500 ml representative core from many locations within each group of trees was collected with a soil probe to a depth of 15 cm. Nutrient data were analyzed with the Bartlett Tree Research Laboratory's soil recommendations software to create a prescription fertilizer program that complied with ANSI A300 standards (Table 5.3).

Fifty soil cores were also collected from each site to determine pre-treatment bulk density. The average pre-treatment bulk density was 1.41 ± 0.02 SE g/cc, with Group 2 soils having significantly higher bulk densities than Group 1 soils.

Experimental Design and Treatment Application

Five treatments (Airspade® tillage (A), fertilizer (F), mulch (M), Root Invigoration™ (AFM) and control (C)) were applied to ten replicate trees in November 2005. Treatments were assigned in a randomized complete block design consisting of 10 replicate blocks with each treatment randomly assigned to one tree per block. Blocks were established based on tree location and visual ratings within locations. Prior to treatment application, all trees were assigned visual ratings from 0-10 by two trained arborists; ratings were based on crown density, leaf color and vigor.

Table 5.1. Pre-treatment properties of red maples in Anderson (N=50).

Parameter	**Group 1**	**Group 2**	**Group 3**	**Sufficiency**[4]
Foliar N (%)	1.4 ± .01	1.5 ± .04	1.8 ± .04	0.9-2.68
Foliar P (%)	0.09 ± .001	0.08 ± .002	0.09 ± .001	0.07-0.42
Foliar K (%)	0.60 ± .02	1.1 ± .15	0.56 ± .01	0.35-1.23
Foliar Ca (%)	0.71 ± .01	0.56 ± .10	0.87 ± .02	0.33-2.24
Foliar Mg (%)	0.16 ± .003	0.13 ± .03	0.23 ± .006	0.10-0.63
Foliar Zn (ppm)	22.0 ± .55	16.8 ± 2.4	31.5 ± 1.4	16-50
Foliar Cu (ppm)	4.9 ± .17	5.4 ± .75	18.3 ± 1.3	3-18
Foliar Mn (ppm)	210.3 ± 9.8	212.6 ± 21.2	606.3 ± 49.2	20-765
Foliar Fe (ppm)	86.1 ± 1.7	150.2 ± 13.4	131.4 ± 2.5	52-683
Foliar S (%)	0.11 ± .0009	0.13 ± .004	0.13 ± .003	0.08-0.21
Foliar Na (ppm)	18.3 ± .48	21.6 ± 1.7	23.9 ± 1.0	20-318
SPAD[1]	37.7 ± .47	35.5 ± 1.8	36.4 ± .56	
DBH (cm)[2]	5.2 ± .11	3.1 ± .39	4.0 ± .16	
Condition[3]	6.9 ± .06	3.4 ± .24	8.6 ± .13	

[1] Mean foliar chlorophyll content measured with Minolta SPAD-502 (Minolta Inc, Japan)

[2] Stem diameter measured with a diameter tape at approximately 1.4 m (4.5 feet) from ground height

[3] Visual analysis based on a 1-10 scale assessing foliage color, crown density, dieback and vigor

[4] Sufficiency ranges for red maple from research plots (Mills and J. Benton Jones, 1996)

Table 5.2. Chemical and physical properties of pre-treatment soil in Anderson.

Parameter[1]	Group 1	Group 2	Group 3
ENR[2] (kg/ha)	128	83	76
Soil P (ppm)	12	171	8
Soil K (ppm)	110	156	150
Soil Mg (ppm)	69	122	147
Soil Ca (ppm)	502	1446	879
Soil Na (ppm)	14	13	14
Sol. Salt (ppm)	0.3	0.3	0.3
Soil Fe (ppm)	49	59	47
Soil Mn (ppm)	54	76	183
Soil Cu (ppm)	2	1.7	1.1
Soil Zn (ppm)	2	5	1.2
Soil OM (%)	1.7	4.6	1.2
Soil CEC (meq/100g)	5.8	9.7	7.7
Bulk Density (g/cc)[3]	1.38 ± .02	1.53 ± .03	1.43 ± .05

[1] Chemical properties based on n=1; Bulk density based on n=30, n=5 and n=15 for Groups 1, 2 and 3, respectively

[2] Estimated Nitrogen Release based on soil organic matter

[3] Mean ± 1 SE

Table 5.3. Fertilizer products applied to each AFM and fertilizer-treated soil area (7.1 m^2).

Product	Analysis	Manufacturer	Application Rate Group 1	Application Rate Groups 2 & 3
Boost Granular	24-7-7 S 6% Ca 1% Fe 0.10% Cu 0.05% Zn 0.05%	F.A. Bartlett Tree Expert Co. Stamford, CT	375 g	470 g
Tiger 90	0-0-0-90 S	Tiger-Sul Products Co Calgary, AB	565 g	
Epsom salt	100% $MgSO_4$	Top Co Associates LLC Skokie, IL	265 g	
Palletized dolomitic lime	21% Ca 11% Mg	ASC Mineral Processing Allerton, IL	1.4 kg	1.4 kg

All trees were treated with Roundup Pro herbicide (Monsanto Company, St. Louis, MO) in a 1.5 m (5 ft.) diameter circle around the trunk 14 days prior to treatment application to eliminate competing vegetation. Weed control was maintained throughout the experiment with additional Roundup applications as needed.

Trees receiving the M treatment were mulched to a depth of 5-7.5 cm (2-3 in.) in a 1.5 m radius around the trunk using 0.45 m^3 (16 $ft.^3$) of bagged, shredded hardwood mulch. Trees receiving the F treatment were fertilized with the materials listed in Table 5.3; these were applied to the soil surface as a granular product or drench within the 1.5 m radius. Trees receiving the A treatment were air-tilled to a depth of 15-20 cm (6-8 in.) using the Air Spade® series 2000 (Concept Engineering Group, Verona, PA) in a 1.5 m radius around the trunk. Controls received no amendment or tillage treatment, but were maintained with a 1.5 m radius vegetation-free zone.

The AFM treatment began with Airspade® tillage as described above. Soils were then amended with 0.28 m^3 (10 $ft.^3$) of bagged, composted cow manure and the prescription fertilizer used in the F treatment. Amendments were applied to the 1.5 m radius and incorporated into the loosened soil profile with the Airspade®. Finally, amended soil received a mulch layer as described for the M treatment.

Because of long-term seasonal drought, application of water was required to prepare the soil for air-spade treatments. All trees received 106 L (28 gals.) of water. Trees receiving AS and AFM treatments received half of the water injected 15 cm beneath the soil surface prior to treatment application and half as a drench following treatment application. All other treatments received the entire volume injected below the soil surface.

Minirhizotron Installation and Sampling

In November 2005, one clear butyrate observation tube (minirhizotron) was installed beneath each of the 50 trees at an angle of 30° from the vertical. The tubes were placed approximately 0.75 m from the trunk. They were 77 cm (30 in.) in length and 5.5 cm (2.2 in.) in outer diameter. Bottoms of the tubes were sealed with acrylic plugs. Light penetration and radiant heating were prevented by wrapping the tops of the tubes in black electrical tape, sealing them with rubber stoppers and covering them with tan aluminum covers. Over the course of two years, some tubes were damaged and had to be removed from the study.

A miniaturized camera system and laptop computer (BTC-2 Minirhizotron Video Microscope and BTC I-CAP Image Capture System, Bartz Technology, Carpinteria, California) were used to capture images of roots that had grown against the minirhizotron tube surface. These images were collected bi-weekly from March through October and monthly during winter. Image collection began 2/21/2006, approximately 3 months after tube installation, and ended on 10/30/2007 for a measurement period of 617 days. Date of appearance, date of death, diameter, length and color were noted for each root in the images using Rootfly software version 1.0.2 (http://www.ces.clemson.edu/~stb/rootfly/, Clemson University, Clemson, SC). Roots were classified as dead when they disappeared or became blackened and shriveled. Diameter and length were measured on each date that a root was observed; color information was also updated on each sampling date.

Statistical Analysis

All statistical analyses were performed using SAS 9.1 (SAS Institute, Cary, NC). Tube level variables (standing crop, production and mortality) were analyzed using repeated measures analysis of variance performed with PROC MIXED. Root demographic parameters (total lifespan, time to browning and brown lifespan) were analyzed using Cox proportional hazards regression performed with SAS PROC PHREG. Root survivorship curves were generated using the BASELINE statement of PROC PHREG.

Demographic data were analyzed using two different PHREG models in order to answer two specific questions. First, using the "discrete" model, the effect of each soil treatment on root lifespan was assessed by testing the effects of 4 separate model covariates, one for each treatment. These covariates took on values of 0 or 1, depending on whether or not a root had received the treatment. For example, a root from a mulch-only tree would have values of 0,0,1,0 for the A, F, M and AFM covariates, respectively. A root from an AFM tree would be coded 0,0,0,1. In this case, a significant P-value for AFM indicates that the AFM treatment altered root lifespan. However, it does not tell us whether this effect was due to the individual components alone, or whether there was an additional benefit to combining the treatments.

The potential synergy among the AS, F, and M treatments was separated from their individual additive effects in a second model (the "aggregate" model) in which AFM was coded as 1,1,1,1. In this case, a significant P-value for AFM indicates that the AFM treatment has an effect beyond the additive effects of its individual components. Hereafter, the two PHREG models will be referred to as the "discrete" and "aggregate" models, respectively.

Some tube level variables were subjected to similar analyses using PROC MIXED to separate additive from synergistic responses. Treatments were coded in the mixed model with covariates as in the aggregate PHREG model.

Results

Root Diameter and Depth Distribution

AFM and mulch treatments reduced root diameter when compared to control (Fig. 5.1; $p < 0.05$). Mean fine root diameter for control was 0.56 ± 0.12 mm, while those of mulch and AFM were 0.52 ± 0.06 mm and 0.50 ± 0.07 mm, respectively. An aggregate model revealed that reduced root diameter in AFM trees was due to more than the influence of mulch alone (aggregate AFM $p = 0.0013$; data not shown).

Treatments also had an effect on fine root depth distribution. After two seasons, AFM and fertilizer trees had shifted the majority of their fine root length to the upper half (0-33.3 cm soil depth) of the minirhizotron, whereas control trees had the majority of their roots on the lower half of the tube (Fig 5.2; $p < 0.05$). AS and M treatments had no effect on this distribution (data not shown).

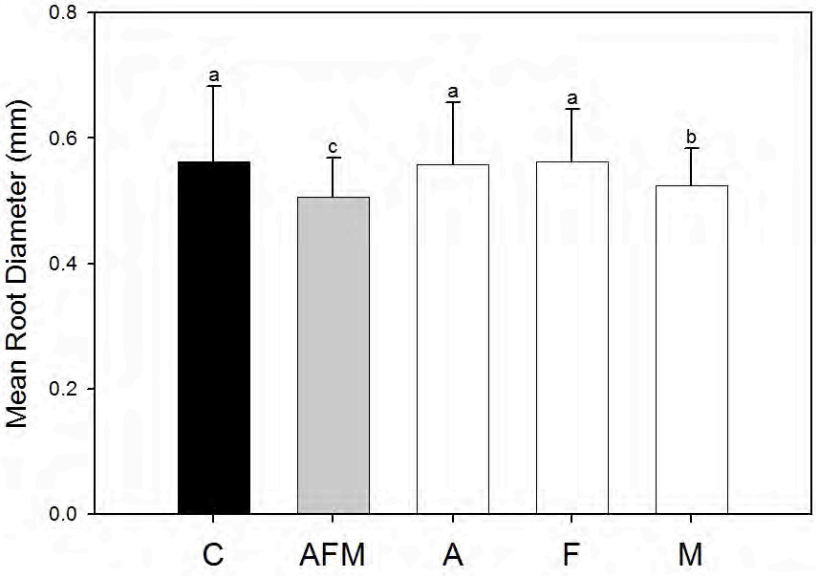

Figure 5.1. Mean root diameter over 2006 and 2007 growing seasons (*n*=8 for C; *n*=9 for A, F and M; and *n*=10 for AFM). Error bars represent one standard error of the mean. Treatment means depicted with different letters are significantly different using Fisher's multiple comparisons procedure ($\alpha = 0.05$).

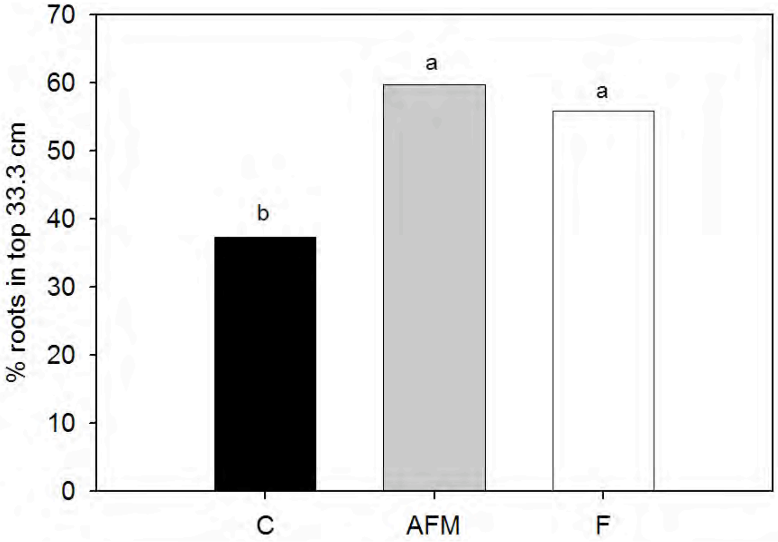

Figure 5.2. Vertical root distribution of red maple in response to soil treatments (*n*=8 for C, *n*=9 for F, and *n*=10 for AFM). Treatment means depicted with different letters are significantly different using Fisher's LSD procedure ($\alpha = 0.05$). A and M treatments not shown since no significant differences with control occurred.

Root Production and Mortality

In general, fine root standing crop was lower in AFM, M and A trees compared to control (Fig. 5.3). However, this difference was only statistically significant on a small number of sampling dates in 2006 and had disappeared in A trees by 2007. Averaged across all 2007 sampling dates, AFM and M trees had 43% and 32% lower standing root crops, respectively. Fertilized trees had higher standing crops throughout most of the experiment, but this trend was never significant.

These trends were also apparent in cumulative root production. AFM, A and M trees had lower cumulative root length production than controls, while F trees had greater production (Fig. 5.4). However, neither cumulative production nor cumulative mortality differed among treatments on any sampling date.

Although there were no overall differences in cumulative production and mortality among treatments, there were differences on individual dates (Fig. 5.5). In 2006, there were three dates where fine root production was significantly higher for controls than AFM, A and M trees. The previous trends of F trees producing more fine roots persists, as controls only produced significantly more fine roots on one date, and F trees often produced more fine root length, although not significant. 2007 resulted in only one significant difference in fine root production, but F trees tended to produce more fine root length on any given date. There were a few isolated differences in mortality data, however no trends were apparent across treatments or years.

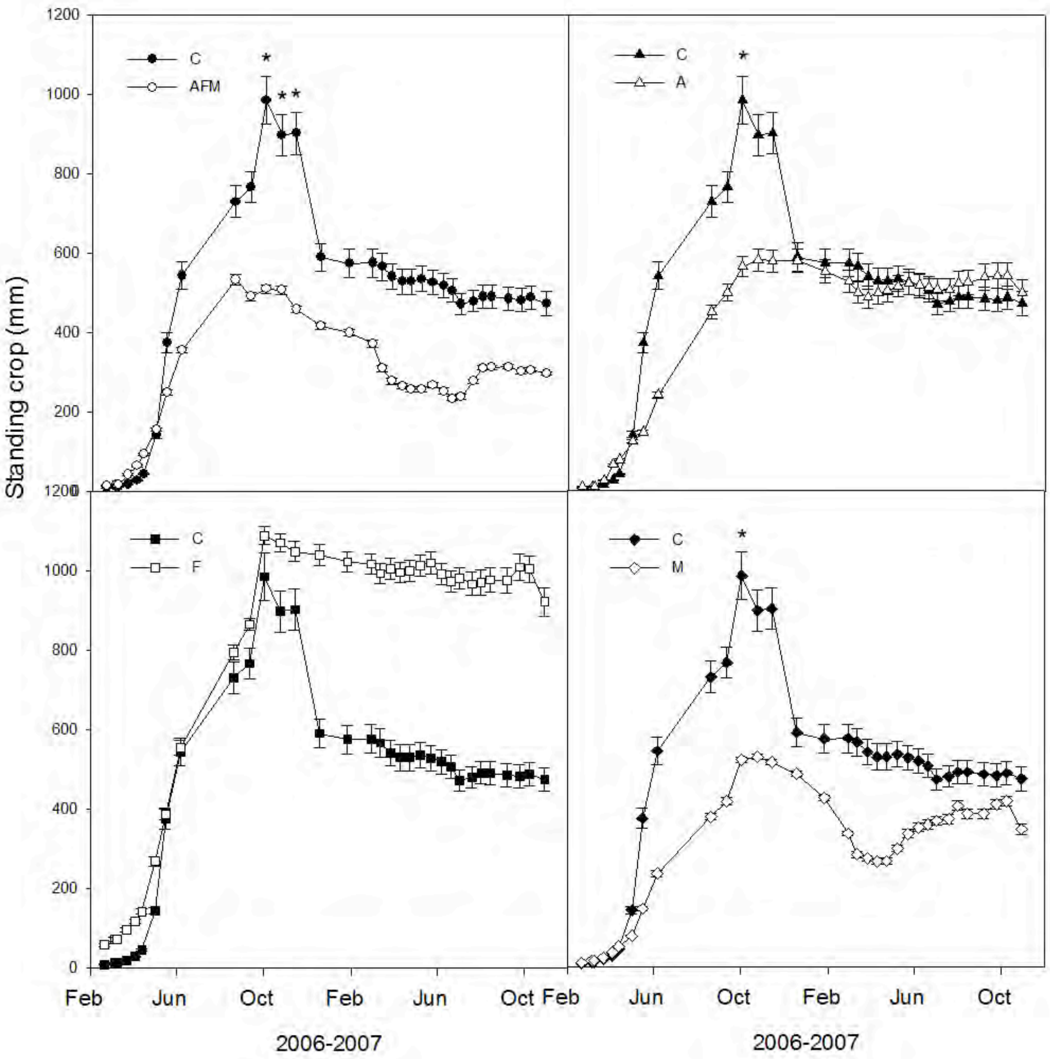

Figure 5.3. Standing root crop of red maple during 2006 and 2007 following soil treatments (*n*=8 for C; *n*=9 for A, F and M; and *n*=10 for AFM). Error bars represent 1 standard error of the mean. *Denotes a significant difference between treatment and control means at $\alpha = 0.05$ using Fisher's LSD procedure.

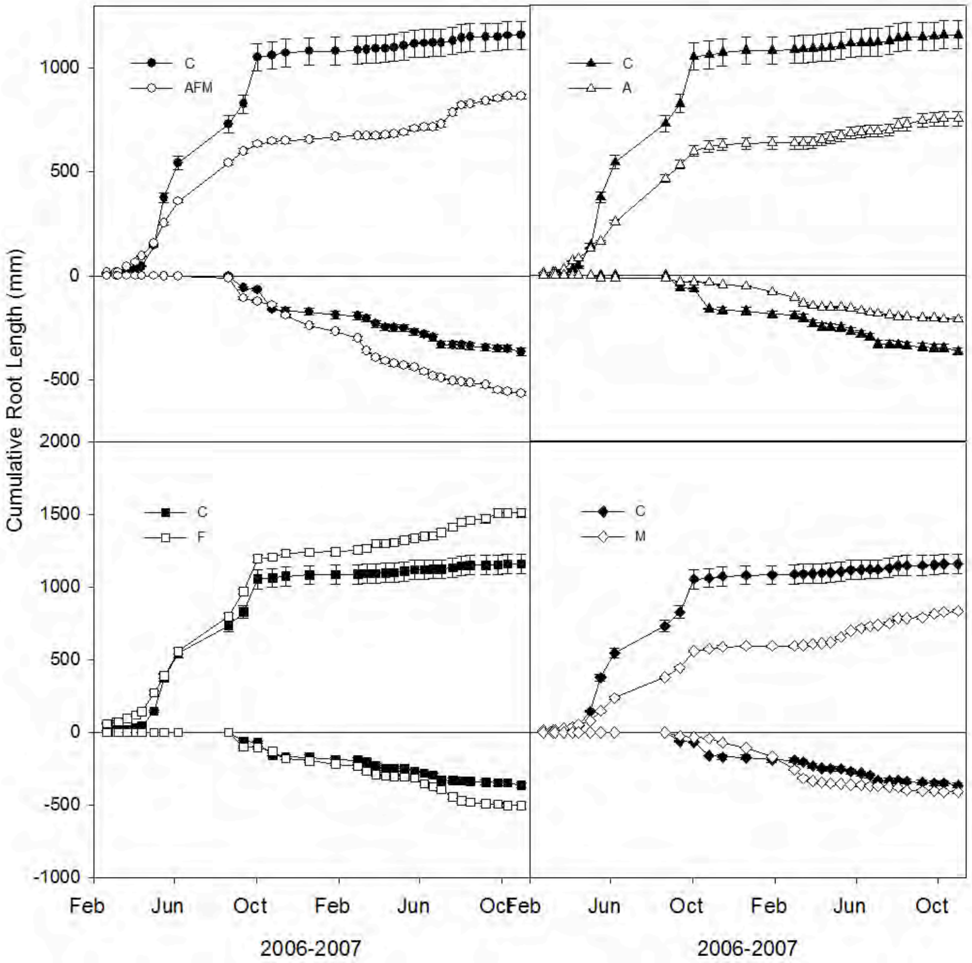

Figure 5.4. Cumulative root production and mortality of red maple during 2006 and 2007 following soil treatments (*n*=8 for C; *n*=9 for A, F and M; and *n*=10 for AFM). Error bars represent 1 standard error of the mean. *Denotes a significant difference in treatment and control means at *α* = 0.05 using Fisher's LSD procedure.

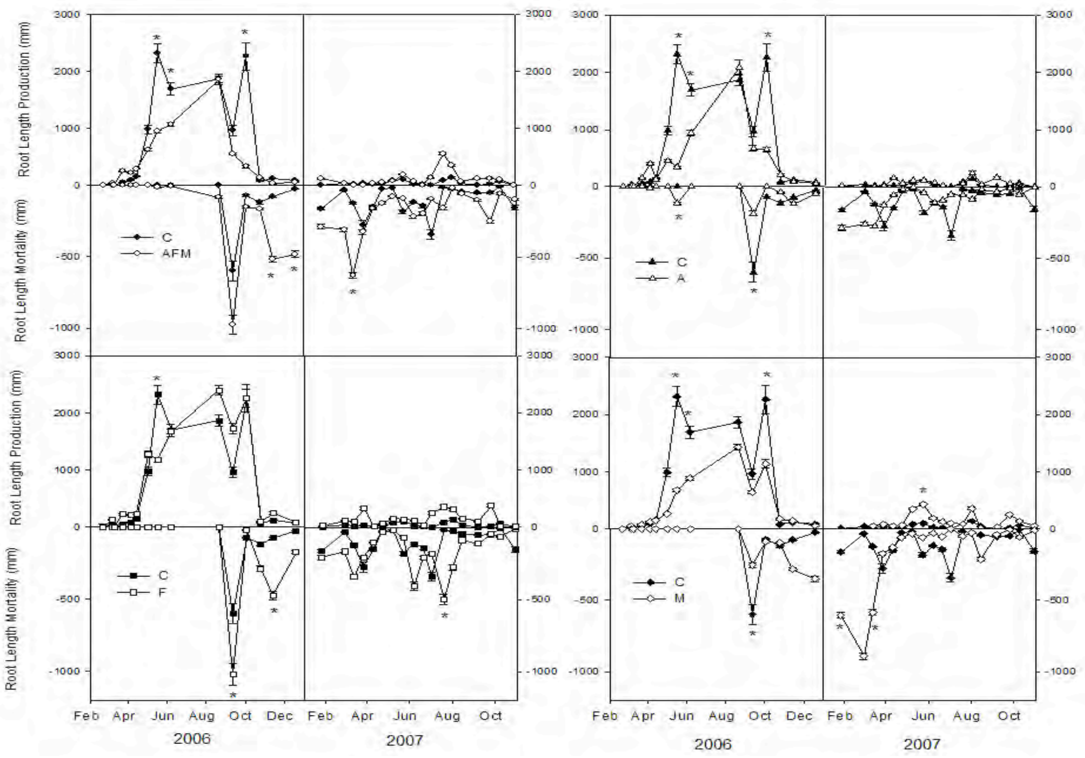

Figure 5.5. Root production and mortality of red maple during 2006 and 2007 following soil treatments (*n*=8 for C; *n*=9 for A, F and M; and *n*=10 for AFM). Error bars represent 1 standard error of the mean. *Denotes a significant difference in treatment and control means at $\alpha = 0.05$ using Fisher's LSD procedure.

Root Lifespan

Median root lifespan ranged from 334 days for control trees to 117 days for AFM trees (Table 5.4; Fig. 5.6 and 5.7). Controlling for the effects of root diameter and depth distribution, total root lifespan was reduced by AFM treatments (Table 5.5; $p = 0.0007$). Mulched roots also had a greater risk of mortality ($p < 0.0001$), while Airspade® and fertilizer treatments had no effect on total root lifespan. Roots that were larger in diameter and deeper in the soil had a reduced risk of mortality ($p < 0.0001$).

Table 5.4. Median lifespan estimates of red maple in response to soil treatments. Data collected from minirhizotron images spanning 2006 and 2007 growing seasons (*n*=8 for C; *n*=9 for A, F and M; and *n*=10 for AFM).

Treatment	**Median Lifespan[1] (days)**	**Median Time To Browning (days)**	**Median Brown Lifespan (days)**
C	334	268	275
AFM	117	96	102
A	416	264	128
F	290	226	191
M	156	117	85

[1] Median lifespans derived from survival probabilities calculated using Cox proportional hazards regression.

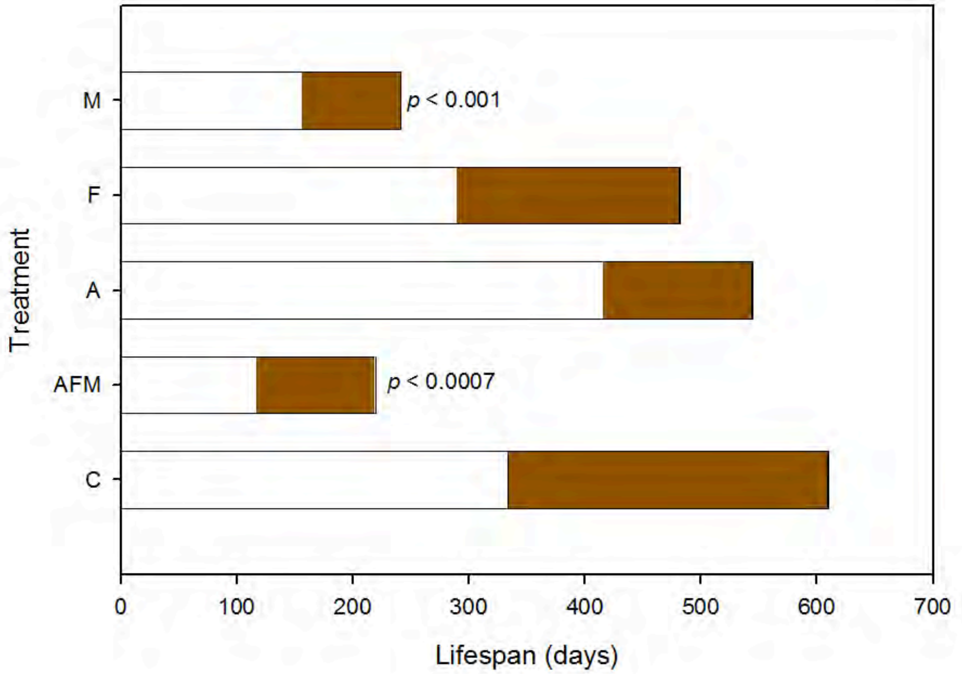

Figure 5.6. Median fine root lifespan represented in days. White portions of graph signify media time until browning, while brown portions of graph represent brown root lifespan. Median lifespans derived from survival probabilities calculated using Cox proportional hazards regression (PHREG). *P*-values denote significant differences using the PHREG aggregate model for total lifespan.

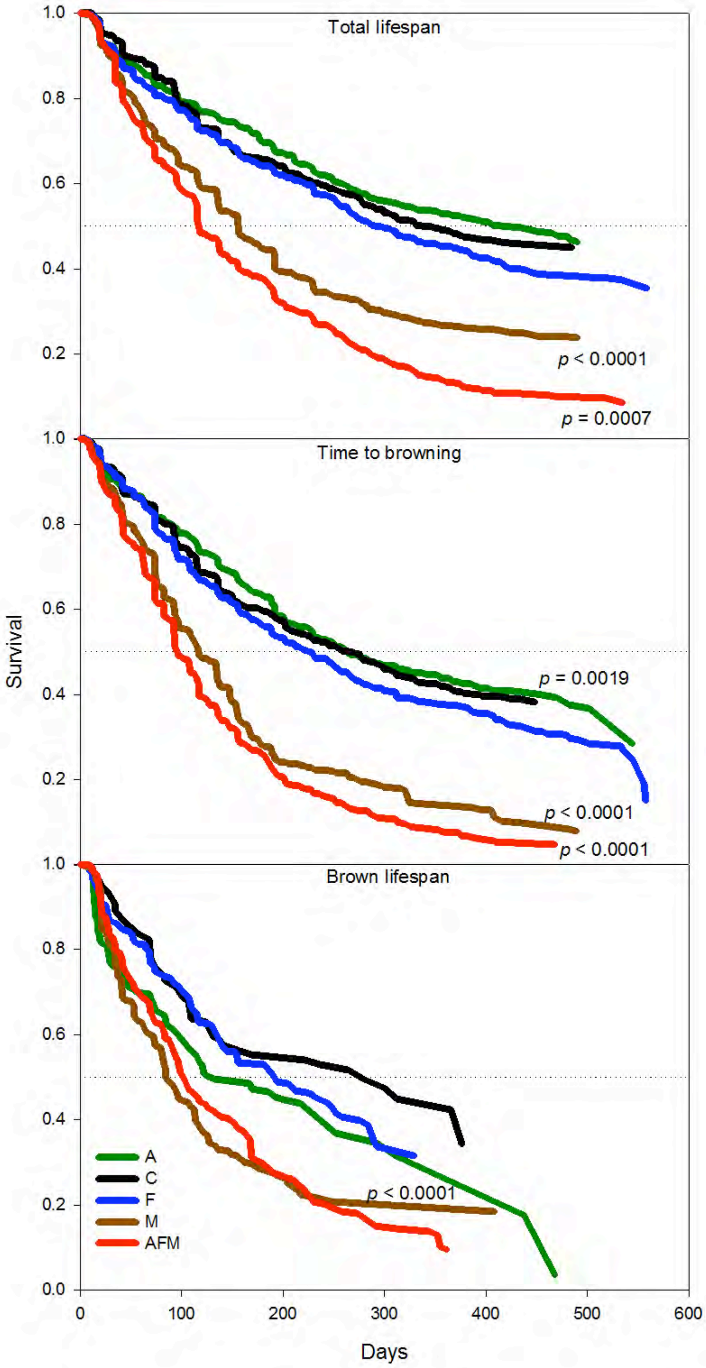

Figure 5.7. Fine root survivorship in red maple throughout 2006 and 2007 growing seasons. Probabilities were calculated using the aggregate model and Cox proportional hazards regression. *P*-values represent treatment significance when compared to mortality risk of control.

Table 5.5. Effect of treatment, root diameter and depth in soil on total root lifespan of red maple during 2006-2007.

Aggregate Model:

Variable	DF	Parameter Estimate	Standard Error	Chi-Square	Pr>ChiSq	Hazard Ratio
A	1	-0.08114	0.06022	1.8158	0.1778	0.922
F	1	-0.01151	0.04744	0.0589	0.8082	0.989
M	**1**	**0.54943**	**0.05152**	**113.7379**	**<.0001**	**1.732**
AFM	**1**	**0.36032**	**0.10605**	**11.5445**	**0.0007**	**1.434**
Root dia.	**1**	**-0.37769**	**0.06722**	**31.5718**	**<.0001**	**0.685**
Depth in soil	**1**	**-0.04091**	**0.00154**	**707.4371**	**<.0001**	**0.960**

Discrete Model:

Variable	DF	Parameter Estimate	Standard Error	Chi-Square	Pr>ChiSq	Hazard Ratio
A	1	-0.08114	0.06022	1.8158	0.1778	0.922
F	1	-0.01151	0.04744	0.0589	0.8082	0.989
M	**1**	**0.54943**	**0.05152**	**113.7379**	**<.0001**	**1.732**
AFM	**1**	**0.81709**	**0.04893**	**278.8398**	**<.0001**	**2.264**
Root dia.	**1**	**-0.37769**	**0.06722**	**31.5718**	**<.0001**	**0.685**
Depth in soil	**1**	**-0.04091**	**0.00154**	**707.4371**	**<.0001**	**0.960**

AFM, Airspade® and mulch treatments increased the risk of root browning (Table 5.6; $p < 0.05$). Root browning occurs as roots age, and this pigmentation is associated with reduced water and nutrient uptake as compared to young, white roots (Wells and Eissenstat, 2001). Root median time to browning was reduced from 268 days for control to 264, 226, 117 and 96 days for A, F, M and AFM treatments, respectively. The aggregate model revealed that the effect of AFM on root browning was due to the individual effects of A and M alone. The risk of browning increased as diameter increased ($p < 0.0001$), but was unrelated to root depth in the soil profile ($p = 0.4825$).

Table 5.6. Effect of treatment, root diameter and depth in soil on time until root browning of red maple during 2006-2007.

Aggregate Model:

Variable	DF	Parameter Estimate	Standard Error	Chi-Square	Pr > ChiSq	Hazard Ratio
A	**1**	**0.37650**	**0.12100**	**9.6814**	**0.0019**	**1.457**
F	1	-0.09966	0.11058	0.8123	0.3674	0.905
M	**1**	**0.69642**	**0.11327**	**37.8041**	**<.0001**	**2.007**
AFM	1	0.09659	0.22860	0.1785	0.6726	1.101
Root dia.	**1**	**0.93388**	**0.06545**	**203.5880**	**<.0001**	**2.544**
Depth in soil	1	-0.00215	0.00306	0.4931	0.4825	0.998

Discrete Model:

Variable	DF	Parameter Estimate	Standard Error	Chi-Square	Pr > ChiSq	Hazard Ratio
A	**1**	**0.37650**	**0.12100**	**9.6814**	**0.0019**	**1.457**
F	1	-0.09966	0.11058	0.8123	0.3674	0.905
M	**1**	**0.69642**	**0.11327**	**37.8041**	**<.0001**	**2.007**
AFM	**1**	**1.06985**	**0.10929**	**95.8229**	**<.0001**	**2.915**
Root dia.	**1**	**0.93388**	**0.06545**	**203.5880**	**<.0001**	**2.544**
Depth in soil	1	-0.00215	0.00306	0.4931	0.4825	0.998

Once brown, the risk of an individual root dying was increased by AFM and mulching (Table 5.7; $p < 0.0001$). The median time until root disappearance was reduced from 275 days for control to 85 and 102 days for mulch and AFM, respectively. However, the aggregate model revealed that AFM only reflects the M effect. Airspade® and fertilizer treatments had no effect of the risk of brown roots dying.

Discussion

We evaluated the effects the Root Invigoration™ (AFM) process on red maple roots and compared these effects to its individual components (A, F and M) and controls.

Table 5.7. Effect of treatment, root diameter and depth in soil on brown root lifespan of red maple during 2006-2007.

Aggregate Model:

Variable	DF	Parameter Estimate	Standard Error	Chi-Square	Pr>ChiSq	Hazard Ratio
A	1	0.21527	0.16376	1.7279	0.1887	1.240
F	1	0.18005	0.15596	1.3328	0.2483	1.197
M	**1**	**0.69736**	**0.15463**	**20.3376**	**<.0001**	**2.008**
AFM	1	-0.48181	0.31466	2.3446	0.1257	0.618
Root dia.	**1**	**-0.66389**	**0.13097**	**25.6957**	**<.0001**	**0.515**
Depth in soil	**1**	**-0.02533**	**0.00385**	**43.3562**	**<.0001**	**0.975**

Discrete Model:

Variable	DF	Parameter Estimate	Standard Error	Chi-Square	Pr>ChiSq	Hazard Ratio
A	1	0.21527	0.16376	1.7279	0.1887	1.240
F	1	0.18005	0.15596	1.3328	0.2483	1.197
M	**1**	**0.69736**	**0.15463**	**20.3376**	**<.0001**	**2.008**
AFM	**1**	**0.61086**	**0.14598**	**17.5111**	**<.0001**	**1.842**
Root dia.	**1**	**-0.66389**	**0.13097**	**25.6957**	**<.0001**	**0.515**
Depth in soil	**1**	**-0.02533**	**0.00385**	**43.3562**	**<.0001**	**0.975**

Minirhizotrons were used to capture information about fine root production, mortality and demographics. We found AFM had few significant effects on production and mortality, particularly in the second season of study. However, F trees tended to produce more fine root length. AFM had a significantly reduced total fine root lifespan, beyond merely the summation of the individual treatment effects. In the case of time until root browning and brown root lifespan however, the AFM influence only reflected the effects of the individual treatments.

Root Production and Mortality

Throughout the 2007 growing season, AFM and M trees had lower standing crop (less root length) than control trees. On the other hand, standing crops of F trees were almost twice as large as control, although these differences were rarely significant. These results were unexpected, as we expected the AFM process to encourage more fine root length production. While the production of greater roots length may seem advantageous due to the increase in surface area for water and nutrient uptake (Eissenstat, 1992), these roots also incur construction and maintenance costs (Hodge, 2004). These costs, coupled with the fact that growth may be reduced outside of the fertilized zone (Hodge, 2004), may reduce the overall benefit of root production.

AFM, M and F treatments had higher levels of root mortality (75.6%, 62.1% and 51.1%, respectively) than controls (43.0%). The combination of increased mortality and reduced production in AFM and M trees led to lower standing crops than control trees. The A treatment also initially had lower standing crops and lower production levels, but also had lower mortality levels (45.5%).

Similar to the current study, King et al. (2002) observed that fertilization increased fine root length production and mortality, while increasing net fine root production. Other studies have observed similar results with increased nitrogen fertility (Burton et al., 2000; Pregitzer et al., 1993; Pregitzer et al., 1995), although others have seen decreases in fine root production (Gower et al., 1992; Grier et al., 1981; Vogt et al., 1986). These inconsistencies are likely due to the differences in methods, genotype, soil attributes and site characteristics.

Beyond these inconsistencies, fertilizer placement (i.e. broadcast or in isolated patches) will likely effect root response. Pregitzer et al. (1993) documented additions of nitrogen into water in patches greatly increased the production of fine roots in the zone surrounding the application. However, other studies evaluating the influence of fertilization on larger soil volumes have shown decreases in fine root biomass with increased fertility (Haynes and Gower, 1995). One must view these production data carefully though, as Hodge (2004) points out that architecture alterations aren't always accompanied by shifts in biomass and often nutrient patch exploitation may result in reduced growth outside the patch.

Soil moisture may also influence fine root dynamics. Soil moisture can increase root length production (Coleman, 2007; Pregitzer et al., 1993), but in other cases has no effect (Majdi, 2001). Our results align more with the latter conclusion in that the AFM and M treated soils had higher levels of soil moisture over the two growing seasons of study (Fite et al., 2008) yet had less root production. However, the AFM and M treatments also had higher levels of soil organic matter (Fite et al., 2008). This organic fraction represents a significant variable in resource availability due to the microbial decomposition and release of inorganic inputs (Hodge, 2004).

Total Root Lifespan

Plants use a large fraction of daily photosynthate to produce and maintain root systems (Eissenstat et al., 2000). As roots die and decompose, they also represent an important component of soil nutrient and carbon cycling (Anderson et al., 2003; Eissenstat and Yanai, 1997; King et al., 2002; Pregitzer et al., 1995). Root lifespan is variable and can even fluctuate largely within a species (Eissenstat et al., 2000). Root lifespan must be thought of in "whole-plant" carbon allocation context, and roots must be considered as only one of the plant's carbon sinks (Pregitzer, 2003).

Since roots are a large carbon cost to the plant, the gains associated with their construction and maintenance should be examined. Roots are remarkably plastic and are able to respond with selective production or mortality to increase productivity (Eissenstat and Yanai, 1997). This plasticity allows for a balance of construction and maintenance costs with resource (i.e. water, nutrients) acquisition. Pregitzer et al. (1993) observed increased lifespan with water and nitrogen treatments. However, this was resource placement in patches. On the contrary, higher soil moisture was shown to increase the risk of root mortality in Concord grape, although not significant at $p < 0.05$ (Anderson et al., 2003). Clearly, this is a complex balance that represents adaptations that we are only beginning to understand.

AFM and M treatments resulted in smaller mean root diameters and shorter root lifespans. Thinner roots have been shown to be more efficient than coarse roots in terms of nutrient uptake efficiency (Eissenstat and Yanai, 1997). Both of these treatments also had higher levels of soil organic matter in 2007 (Fite et al., 2008). Craul (1985; 1992) states that increased levels of organic matter are a major source of energy for soil organisms and lead to a healthy soil environment for root growth. As organic tissues are decomposed by soil microbes, energy is used and complex compounds are transformed into simple compounds and mineral nutrients for root uptake (Craul, 1992; Harris et al., 2004). Perhaps the combination of smaller diameter roots and the potential for more nutrient cycling led to the decreases in lifespan. Our results echo others in that roots of small diameter have higher mortality rates than those of larger diameter (Baddeley and Watson, 2005; Pregitzer, 2003; Wells and Eissenstat, 2001).

Not only is root lifespan influenced by diameter, but also by vertical distribution in the soil profile. With increasing root depth, we observed decreasing risks of mortality. Anderson et al. (2003) and Baddeley and Watson (2005) observed similar results and hypthesized that deeper roots may have reduced exposure to soil moisture and temperature fluctuations or experience less herbivory. AFM and M treatments had higher levels of soil moisture frequently throughout the study (Fite et al., 2008). Moist soils have been shown to both reduce and increase root lifespan (Anderson et al., 2003; Bryla et al., 1997; Kirkham et al., 1998; Pregitzer et al., 1993).

A and F treatments had no effect on root lifespan. Although the same fertilizer was applied to the F-treated soils as the AFM-treated soils, levels of mineral nutrients in the F soils didn't differ from control, but AFM levels were different (Fite et al., 2008). The AFM nutrient levels were undoubtedly enhanced with the incorporation of additional organic matter. The lack of increase in nutrient concentration may explain the lack of response anticipated from fertilized soils.

Time To Browning

Root browning is associated with a reduced capacity for water and nutrient uptake. Time until root browning represents the time that a root is in a highly-active, white state. The A and M treatments were the only treatments to significantly reduce time until root browning. The AFM treatment was significant in the discrete model, but the aggregate model illustrated that this was only a reflection of individual treatment effects. With both A and M treatments, roots had a higher risk of turning brown. Pigmentation of roots has been associated with the reduced capacity of water and nutrient uptake (Anderson et al., 2003; Comas et al., 2000; Head, 1966; Wells and Eissenstat, 2001).

Root diameter affects time until browning differently than it affects total lifespan. The risk of a root browning is significantly increased with root diameter, whereas the risk of a root dying is decreased with diameter. Our results agree with those of Wells and Eissenstat (2001), as they found apple roots of small diameter were less likely to brown and had higher risks of mortality.

Brown Lifespan

Mulch was the only treatment to significantly affect brown root lifespan. AFM was significant in the discrete model, but the aggregate model exposed that this was due only to the effect of mulch. Mulch significantly increased the risk of death after a root has become pigmented. This could be a function of increased soil organic matter content promoting root decomposition. Although AFM soils had equal levels of organic matter, those soils were also higher in nutrient concentrations (Fite et al., 2008). The roots in the AFM soils may have higher tissue nutrient concentrations and take longer to decompose.

Conclusions

Root systems of F-treated trees developed more root length compared to controls, while other treatments did not. However, F had no effect on total root lifespan, time until root browning and brown lifespan. AFM increased the risk of root mortality beyond the increase attributed to mulch alone. However, M also decreased the time until root browning and was responsible for this decrease for the AFM treatment. The A treatment also decreased time until root browning, suggesting that different portions of the root lifecycle may be controlled independently. Studies involving other species and soils are needed to strengthen these findings.

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CHAPTER VI

SUMMARY

Introduction

We've all seen them—victims of urban soil. Poor trees placed in cut, filled, mixed, contaminated and compacted soils, expected to live and thrive, yet struggling merely to survive. What happened to them? More important, is there anything we can do?

The urban soil environment is a tough one for roots. Low levels of organic matter and mineral nutrients—coupled with high levels of compaction—result in poor root growth. Physical compaction of the soil not only makes it difficult for roots to grow, but also exacerbates drought and flooding because of improper pore space distribution. Nutrient deficiencies occur when extensive root systems cannot develop and are made worse by low organic matter and nutrient concentrations in the soil.

The Root Invigoration™ program was designed to rehabilitate urban soils and improve tree performance, while limiting damage to established root systems (Figures 6.1 & 6.2). This is accomplished using a compressed air excavation tool to till the soil and break up the compaction in the upper soil layer where most fine feeder roots are located. Organic matter and prescription fertilizer amendments are then added to the loosened soil and worked in with the air tool. Finally, the treated area is mulched and watered to prevent drying and to settle the soil.

Since 2005, we have been testing the effects of Root Invigoration™ and its individual components (mulch, fertilizer and Airspade® tillage) on declining red maple

Figure 6.1. Soil beneath red maple tilled with Airspade® and amended with fertilizer and compost before (incorporation into soil profile).

Figure 6.2. Incorporation of amendments into the soil profile using the Airspade®.

trees (*Acer rubrum*) at four urban sites in the eastern United States (Anderson, SC; Myrtle Beach, SC; Boston, MA and Pittsburgh, PA). Our goal was twofold: 1) to document the effects of Root Invigoration™ and 2) to establish if any single component of the process gives results similar to the comprehensive program. Fifty trees at each site received either Root Invigoration™, mulch only, granular fertilizer only, air tillage only, or no treatment. The sites represented a range of "real world" urban environments: a golf course, a college campus, a civic center parking lot and an urban roadside planting. Treatments were applied between August 2005 and February 2006 and the results were monitored through November 2007.

Soil Responses

The changes that occurred below-ground were exciting. Soil strength, nutrient content, organic matter levels and soil moisture were all improved with Root Invigoration™. None of the individual treatments could match this response, although in some cases they improved a single parameter.

Across all sites, Root Invigoration™ reduced the soil's resistance to root penetration ("soil strength") for two seasons following treatment, whereas mulch and Airspade® only reduced soil strength for one season (Fig. 6.3). Lower soil strength means that roots can more easily penetrate Root-Invigorated soils and experience a soil environment that is more conducive to water, nutrient and oxygen uptake. This result stresses the importance of both organic amendments and an appropriate mulch layer when rehabilitating poor soils.

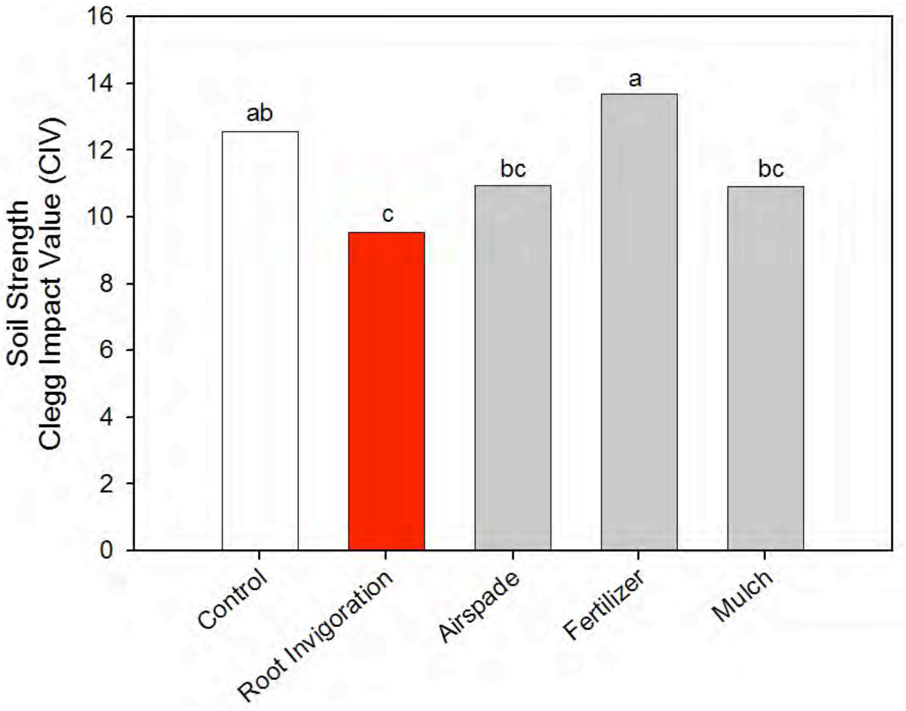

Figure 6.3. Soil strength two seasons following treatment. Treatments with different letter are significantly different from one another using Fisher's LSD test.

The soil organic matter content was increased by both mulching and Root Invigoration™ (Fig. 6.4). Organic matter in urban soils is a major source of energy for soil organisms that contribute to an overall healthy soil environment; its breakdown releases essential nutrients and improves soil structure.

Levels of phosphorus, potassium, magnesium, manganese, boron and zinc were all increased in Root Invigorated™ soils. Surprisingly, only manganese levels were increased by a surface application of the same fertilizer, indicating that the comprehensive soil rehabilitation program was far more effective in providing nutrition to the root zone.

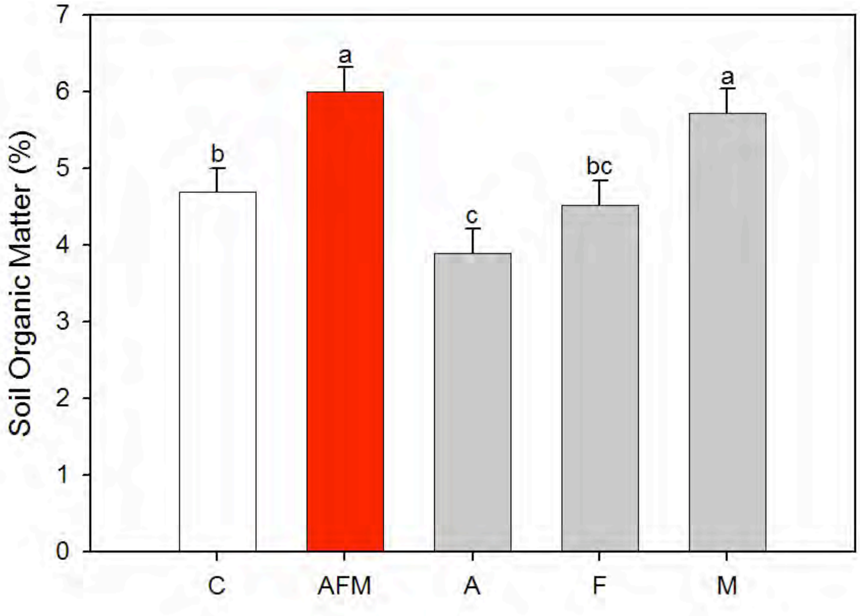

Figure 6.4. Soil organic matter content in spring 2007. Treatments with different letter are significantly different from one another using Fisher's LSD test.

Soil moisture (measured only at the Anderson site) and was higher in mulched soils (Root Invigoration™ and mulch only) than in unmulched (Airspade® only, fertilizer only and controls). Across 2006 and 2007, mulched and Root Invigorated soils had 26% higher soil moisture than unmulched soils, which lowered tree water stress (see "Tree Response" below).

Tree Response

The above-ground response was slightly less stirring; however positive benefits were observed. Root Invigoration™ improved tree condition at all sites, increased diameter growth at two sites and reduced water stress in Anderson. As was the case with the below-ground parameters, no individual treatment could equal all of these positive benefits.

By the end of the second growing season, Root Invigorated trees had higher visual condition ratings than all other trees. This indicates those trees had denser, greener canopies with a healthier appearance. Diameter growth was also increased by Root Invigoration™ at two sites, a result not seen with any other treatment

Plant water stress was measured at the Anderson site in the summers of 2006 and 2007. The end of summer 2007 was classified as extreme drought by the National Weather Service Palmer Drought Severity Index. During this extreme drought, trees of the mulched treatments were experiencing approximately 30% less moisture stress than controls as a result of the increased soil moisture levels (Fig. 6.5).

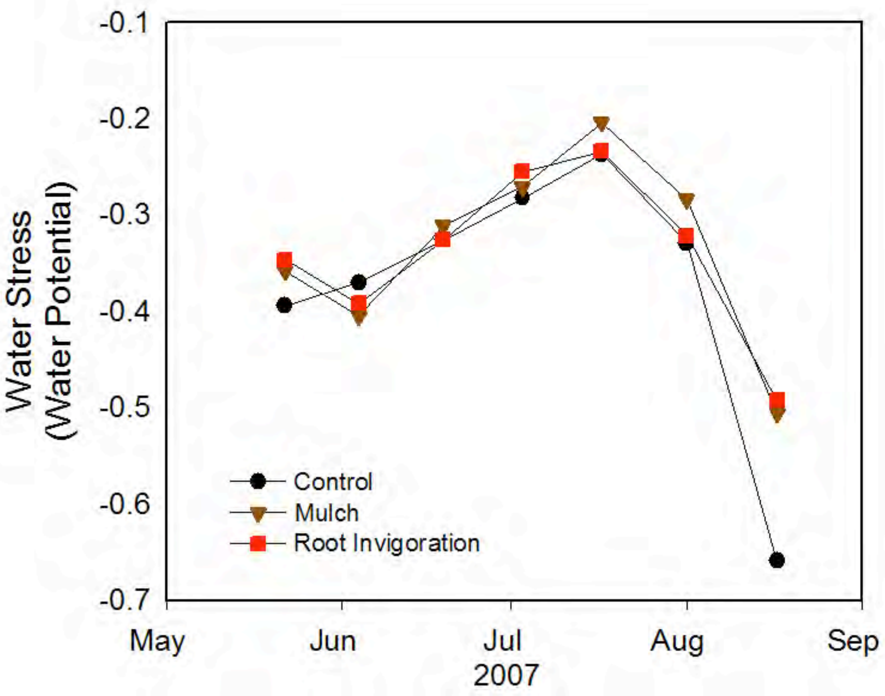

Figure 6.5. Water stress of trees in 2007 growing season. Smaller (more negative) number represent more water stress. Airspade® and fertilizer treatment not shown because they were never different from controls.

Summary

At last, it appears that there is a program available to arborists that will allow trees to be set free from the grasp of the urban soil. All of the factors presented indicate that the use of comprehensive soil amelioration programs like Root Invigoration™ appear to be beneficial for red maple. The next phase of study should focus on the response of other age classes and species to these types of processes.