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Strategic Mulching of Trees in Forested Urban Parkland for Rooting Medium Amendment

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STRATEGIC MULCHING OF TREES IN FORESTED URBAN PARKLAND FOR ROOTING MEDIUM AMENDMENT

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Strategic mulching of trees in forested urban parkland for rooting medium amendment

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Abstract

Trees planted along city streets and in urban parks are subject to many adversities that affect growth and can often result in mortality. The application of organic mulch to the rooting medium of newly planted urban trees has the potential to improve the soil chemical and physical properties necessary for tree root health. This study examined the difference in soil nutrient supply rates (µg/10cm^2/28 days) between three areal treatments of wood chips (0.75 m, 1.0 m and 1.5 m radii) and before mulch application versus after mulch application using Analysis of Covariance. PRS^{TM}-Probes were inserted into the soil over six 28-day periods to measure the supply rate of bioavailable nutrients (NO_3^-, NH_4^+, P, K, S, Ca, Mg, and Cu). Meteorological data and other soil chemical and physical factors were measured and included as covariates in the statistical model. Results indicate that mulching had a significant effect ($p<0.05$) on P supply rates; supply rates were lower in the reference plots compared to the treatment plots post-mulching. S, Ca, Mg, and Cu supply rates decreased after mulch application; however, the decrease was observed in all plots, which is likely due to temporal variations in plant demand rather than mulching. The wood chips also had a significant impact on buffering fluctuating soil temperatures and reducing soil moisture loss compared to non-mulched plots. The knowledge obtained from this research can be used to improve urban forest management strategies by providing a more in-depth understanding of the prescriptive use of organic mulch.

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CHAPTER 1

1.1 Introduction

Trees are an integral part of the urban environment and play an important role in defining the city landscape. Within populated areas, trees are referred to as the "urban forest", which includes "trees along city streets, in parks, ravines and natural areas, front and backyards of homes, and in landscaped open spaces" (City of Toronto, 2010). Several beneficial attributes of trees growing in urban areas include: improved air quality (serving as a sink for carbon dioxide and other greenhouse gases), moderation of air temperature and associated mitigation of the urban heat-island effect (through evapo-transpiration and shading), soil erosion control, reduction of storm water run-off (water retention in the rooting zone), provision of wildlife habitat, beautification of parks and recreational spaces, and aesthetic enhancement of private property (Trowbridge and Bassuk, 2004; Roberts *et al*., 2006; Millward and Sabir, 2010).

In 2004, the City of Toronto adopted a plan to double its urban forest canopy to between 30-40 percent within the next 50 years. At this time, the forest canopy had been estimated to cover only 17-20 percent of the city; however, more recent statistics indicate the canopy cover is actually 26-28 percent, covering an area of 17,000-18,000 ha (City of Toronto, 2012). Currently, the average tree diameter in Toronto is 16.3 cm and only 14 percent of trees have a diameter greater than 30.6 cm. This has implications on the structural and functional values of these trees as larger, mature trees can intercept more air pollution, store a greater amount of carbon, and contribute significantly to the City's tree canopy compared to young trees (City of Toronto, 2010). Despite recognition of the value of trees in the cityscape, most urban areas, including Toronto, have failed to provide the necessary soil conditions for trees to grow to maturity –

nullifying the potential to fully realize their ecological and aesthetic benefits (Millward and Sabir, 2010).

The soil supporting the urban forest in densely built cities is frequently compromised by shallow depth, heavy compaction from vehicular and pedestrian traffic, and impervious surfaces. These factors significantly impact the growth of roots and the stability of the tree, with the latter two also limiting soil water infiltration due to reduced porosity leading to increased plant moisture stress. High temperatures, inadequate organic matter content, poor nutrient availability, and contamination from air, construction, and motor vehicle pollutants are additional concerns for urban trees. These factors alter the physical and chemical properties of soil, which negatively impact the growing conditions for trees (Craul, 1999; Trowbridge and Bassuk, 2004; Day *et al*., 2010).

Application of organic mulch to the soil surface covering the rooting zone of newly planted and mature urban trees can dramatically improve their survival and long-term health (Litzow and Pellett, 1983; Green and Watson, 1989). Organic mulches improve urban soil conditions by supplying nutrients, increasing soil moisture retention, increasing organic matter content, controlling surface temperature fluctuations, reducing soil compaction, and suppressing weeds (Lal, 1974; Watson, 1988; Duryea *et al*., 1999; Iles and Dosmann, 1999; Rivenshield and Bassuk, 2007).

Trees growing in urban parks provide an opportunity for cities to expand their total canopy cover and establish improved growing conditions for newly planted trees. Parks cover large areas and have the necessary characteristics, such as sufficient soil volume and quality, for roots to expand and flourish (Trowbridge and Bassuk, 2004). Conversely, streetscape trees are usually confined to small pockets of soil and are restricted in growth by overhead utility wires and the surrounding impervious surfaces. Therefore, developing strategies, such as mulch application, to further improve the soil conditions in urban parklands offers a viable means for cities to promote the continued growth of mature trees and ensure those that are newly planted can reach the same health and longevity (Millward and Sabir, 2010).

1.2 Thesis Objectives

The overall goal of this research project is to investigate the effect of different mulching applications on the chemical and physical soil characteristics important for tree root health. This project is a collaboration between Ryerson University's Urban Forest Research & Ecological Disturbance (UFRED) Group and professional arborists from Bruce Tree Expert Company. Specifically, the areal coverage of three mulch applications (i.e., 0.75 m, 1.0 m and 1.5 m radii) was tested using replicate treatment plots and corresponding un-mulched rooting zones (references). Soil nutrient availability was the primary focus of this research, and was measured over a six month period during the growing season. The three main objectives of this thesis were:

(i) Measure soil physical and chemical characteristics within the study area tree rooting zones that are known to affect soil nutrient availability;

(ii) Assess soil nutrient availability and soil physical properties for baseline (pre-mulch) soil conditions versus post-mulch conditions; and,

(iii) Compare soil nutrient availability and soil physical properties between treated (mulched) and non-treated (non-mulched) tree plots and among the three treatment types (mulch radii).

While the use of organic mulch to improve soil conditions is not novel, few studies have investigated how to optimize its areal application in order to maximize soil benefits for urban trees. It was expected that the application of mulch would improve the soil conditions necessary for the growth of urban trees compared to non-treated plots (references), and that the largest radii of mulch (1.5 m) would provide greater soil benefits (i.e., buffer a larger volume of soil against fluctuations in temperature, provide more consistent soil moisture, and provide a greater volume of soil with favourable conditions for bioavailable nutrients). It was also hypothesized that nitrate (NO_3^-) and ammonium (NH_4^+) supply rates would initially decrease under mulched plots due to the high carbon to nitrogen ratio (C:N) of the wood chips, which typically leads to competition from microbes for available nitrogen. Such knowledge will contribute to the discipline of urban forestry by providing a more in-depth understanding of the prescriptive use of organic mulches to improve the survival and long-term health of trees in urban areas.

1.3 Thesis Outline

This thesis is organized into four chapters. In Chapter One, a general background of the research is provided, along with an overview of the objectives of the study. Chapter Two provides an in-depth literature review of the importance of urban trees, the challenging soil conditions they face in urban environments, and the use of organic mulch as a soil amendment. This chapter sets the stage for the remainder of the thesis and identifies the gaps that are currently found in the literature. Chapter Three includes an abbreviated study introduction, methods, results, and discussion; it is formatted as a standalone manuscript for submission to a journal (to be decided at a later date). The final section, Chapter Four, provides a more site-specific discussion and includes a summary of the limitations of the study, the significance of the results, and opportunities for future research. In the Appendices, figures and tables are included that document all soil chemical and physical details.

CHAPTER 2

2.1 Soil Nutrients

Soil nutrients are essential for the healthy growth of trees and can be grouped into two categories: macronutrients and micronutrients. Macronutrients are required in larger quantities and include: nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg). Micronutrients are required in smaller quantities and include: manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), nickel (Ni), molybdenum (Mo), boron (B), and chlorine (Cl) (Trowbridge and Bassuk, 2004; Broadley *et al*., 2012; Hawkesford *et al*., 2012). All soil nutrients can be harmful to the health of trees at concentrations above their physiological requirements; however, in urban environments many of the essential nutrients are found in very low concentrations, which can impair growth and make trees more susceptible to disease, insect infestations, and moisture stress (Craul, 1992; Roberts *et al*., 2006; Day *et al*., 2010). Additionally, there is often little organic matter present in the top layers of urban soil, which is an important source of N, P, S and other nutrients (Roberts *et al*., 2006). In terms of fertility requirements, a common tree species found in Toronto such as northern red oak (*Quercus rubrum*) is able to tolerate low nutrient concentrations. Most maples (*Acer* spp.) are intermediate in their nutrient requirements, except sugar maple (*Acer saccharum*), which is comparatively high. White ash (*Fraxinus americana*), also common to Toronto parks and ravines, has high nutrient requirements, especially for N, P, K, Ca, and Mg (Craul, 1992).

2.1.1 Nitrogen

N is one of the main nutrients that is often limiting in urban soils. The majority of N found in soil is present in its organic form and must be converted to ammonium (NH_4^+) or nitrate (NO_3^-), mainly by microbes, before being absorbed by roots (Roberts *et al*., 2006). The amount of N available in the soil is a reflection of the rate at which N is immobilized by microbes and the rate at which N is mineralized through decomposing organic matter, which is the main source of N in soils (Craul, 1992; Stinner *et al*., 2002). N is the nutrient required in the greatest quantity in plants and is extremely important in the production of amino acids, proteins, nucleic acids, and other N-containing compounds. When N is deficient in soils, symptoms such as stunted growth, narrow leaves, chlorosis, and leaf senescence are commonly observed (Hawkesford *et al*., 2012).

The chemical reactions required to convert N into amino acids occur via a four-step process when NO_3^- is the source of N or a two-step process when NH_4^+ is used (Hull and Bushoven, 2007). Thus, NH_4^+ is a more energy efficient and favourable form of N compared to NO_3^-; however, NO_3^- is more mobile in soils, making it more available for plant uptake (Miller and Cramer, 2004). The conversion process begins when NO_3^- is reduced to NO_2^-, which occurs in the cytosol of leaf or root cells (the intracellular fluid). Then, NO_2^- is reduced to NH_4^+ in the chloroplasts of leaf cells or the leucoplasts of root cells. At this point, the assimilation of NH_4^+ occurs, in which the amino acid, glutamine, is produced through the binding of NH_4^+ to glutamic acid. The final step involves the re-production of glutamic acid to ensure the previous reaction can continuously occur (Hull and Bushoven, 2007).

2.1.2 Phosphorus

P is typically found in low concentrations in most soils and is often bound to soil particles or other molecules, rendering it unavailable (Roberts *et al*., 2006). In acidic soils, P forms compounds with Fe, Al and Mn, and in alkaline soils, it forms precipitates with Mg, Ca, and Al (Otheino, 1973; Hull, 1997b). P can be present in four different inorganic forms depending on the pH of the soil. The two most common forms are the dihydrogen phosphate ion ($H_2PO_4^-$), found in slightly acidic soils, and the monohydrogen phosphate ion (HPO_4^{-2}), found in slightly alkaline soils. Additionally, P can be present in an organic form, but in order to be absorbed by plants, the roots or microorganisms in the soil must excrete an enzyme called phosphatase that hydrolyses the organic P to inorganic P (Hull, 1997b).

Once inside the plant, P is very mobile and is transported to areas where it is needed most (i.e., for growth). One of the most important uses of P is when it is converted to ATP, which occurs when three phosphates attach to adenine and ribose (Hull 1997b). Additionally, P is also the main component of phospholipids in cell membranes, and it plays an important role in the structure of DNA and RNA by forming phosphate bridges between ribonucleoside units (Hawkesford *et al*., 2012). It is also essential in the conversion of NH_4^+ to amino acids – if an ATP molecule attaches P to glutamic acid, which reacts with NH_4^+ to produce glutamine, the reaction is much more energetically favourable and occurs more frequently (Hull, 1997b). Symptoms of P deficiency include: decreased shoot to root ratios, reduction in leaf growth and the number of leaves, premature leaf senescence, and the formation of anthocyanins in the leaves and stems due to the accumulation of sugars (Hull, 1997b; Hawkesford *et al*., 2012). When P levels are low, root growth is stimulated over leaf growth to enable roots to find more available P, which is the opposite of what occurs for N (Hull 1997b).

2.1.3 Potassium

K is an essential nutrient required in several plant metabolic and physiological processes including: photosynthesis, activation of enzymes, water regulation, uptake of N, respiration, and protein synthesis (Lui *et al*., 1996; Cakmak, 2005). K is also known to play an important role in mitigating environmental stress conditions, such as maintaining healthy levels of Na and Fe when the soil solution is highly saturated or saline. Plants that are K deficient exhibit signs of leaf chlorosis and necrosis, high sensitivity to light, a significant reduction in net photosynthesis, and are more susceptible to parasitic attack (Cakmak, 2005; Huber *et al*., 2012).

K input into the soil is primarily from weathering and leaching of soil minerals, especially igneous and sedimentary rocks. Soils with higher clay content typically have a greater amount of total K compared to sandy or loamy soils. In order to be taken up by plant roots, K^+ must be present in the soil solution where a concentration gradient is formed to allow K^+ to move into the root by diffusion (Gourley, 1999).

2.1.4 Sulfur

The form of S required for uptake by plant roots is sulfate (SO_4^{-2}), which is formed when organic S is mineralized to inorganic S and then oxidized. The mineralization of organic S is predominately carried out by soil microorganisms; thus, the environmental factors that affect these organisms (i.e., temperature, moisture, and pH) will affect the rate at which bioavailable S is taken up by plant roots (Lewis, 1999). Once inside plant tissue, S is used to form S-containing amino acids, such as cysteine, and S-containing enzymes, co-enzymes, and secondary compounds necessary to detoxify acids. S deficiency can result in reduced shoot to root ratio, smaller leaf area, chlorosis, and a large decrease in chlorophyll and protein concentrations (Hawkesford *et al*., 2012).

2.1.5 Calcium

Ca is a macronutrient that is typically abundant in most soils, especially in neutral and alkaline soils where carbonate is present (Bruce, 1999). In acidic or Ca deficient soils, a liming solution is often used to increase Ca concentrations; this also increases the soil pH level. Although, Ca levels are generally high in the soil solution, uptake by plant roots mostly occurs through passive transport because Ca is absorbed by roots at a slower rate than the water in which it is dissolved (Hull, 1997a). If Ca deficiency does occur, shoot and root growth of the plant stop, leaf chlorosis and necrosis occurs, and cell wall structures are unable to develop (Hull, 1997a; Bruce, 1999).

In the plant, most Ca is located in the apoplasm and serves to stabilize the cell wall and cell membrane by linking pectin chains together. It is also important in root growth and elongation, osmoregulation, and as a means of signalling plants to regulate development processes in response to environmental stimuli, such as a pathogen attack, low temperature, and high salt concentration (Craul, 1992; Hull, 1997a; Hawkesford *et al*., 2012). When a stressor is present, cell wall damage may occur, and the Ca found in cell walls may be released into the cytosol. A high level of Ca in the cytosol is dangerous because it can compete with Mg and form precipitates with P. When this occurs, a signal is released that triggers a series of reactions within the cell to respond to the stressor (Hull, 1997a).

2.1.6 Magnesium

Mg is the central atom in the chlorophyll molecule and plays an important role in several enzyme catalytic reactions, such as increasing the efficiency of ATP phosphorylation. It also serves as a regulator of pH in the cell, and is required in the formation of bridges between ribosome subunits in protein synthesis. When Mg is deficient, protein synthesis ceases due to the disintegration of the ribosome subunits. Additionally, the size, structure and function of chloroplasts are affected, along with electron transfer in photosystem II (Hawkesford *et al*., 2012). Leaves develop yellow spots between veins, which is more pronounced in older leaves (Craul, 1992). The amount of biologically available Mg in most soils is low, with the majority of Mg present in primary and secondary minerals or organic matter. Uptake of Mg^{+2} can further be reduced by competition for cation exchange sites from other ions such as, NH_4^+, K^+, Ca^{+2}, Mn^{+2}, and Al^{+3} (Aitken and Scott, 1999).

2.1.7 Iron

Fe is a required micronutrient for several plant processes, especially the formation of chlorophyll. Although Fe is not a component of the molecule, it is a cofactor for three reactions necessary for chlorophyll synthesis. Thus, without Fe, chlorophyll is not produced, leading to leaf chlorosis (Hull, 1999). Fe also plays an important role in electron transfer in both the photosynthetic and respiratory electron transport chains as a component of cytochrome and iron-sulfur proteins (e.g., ferredoxin). Additionally, Fe is present in the enzymes, superoxide dismutase, ascorbate peroxidase, and catalase, which are required in the chemical reactions that detoxify oxygen free radicals (Hull, 1999; Broadley *et al*., 2012). Without Fe, these enzymes cannot perform their function, resulting in membrane damage in cell chloroplasts and mitochondria. Fe also aids in the peroxidation of membrane lipids and has been known to help plants develop resistance to the onset of disease (Hull, 1999).

Although Fe is often found in sufficient quantities in most soils, it is often present in forms unavailable for plant uptake. Fe exists in two states: oxidized Fe^{+3} (ferric) and reduced Fe^{+2} (ferrous). In aerobic soils, most Fe is present as Fe^{+3}; however, these ions readily react with phosphate, sulfate and hydroxide radicals to produce insoluble salts that are unavailable to plant roots (Hull, 1999). Instead, plants must utilize Fe from chelates, specifically ferric hydroxide ($Fe(OH)^{+2}$ or $Fe(OH)^{-4}$) in acidic and alkaline soils, respectively. Soluble Fe is found in larger concentrations in acidic soils compared to neutral and alkaline soils (Hull, 1999; McFarlane, 1999).

2.1.8 Manganese

Mn is an important micronutrient involved in several cellular processes. One of its main functions is to strip electrons from the oxygen in water molecules in Photosystem II of the photosynthetic electron transport chain (Hull, 2001b). Mn also plays a role in root elongation and initial lateral root growth, and it is a cofactor of several major enzymes that catalyze oxidation-reduction reactions, decarboxylation and hydrolytic reactions, the destruction of superoxide, and many processes in the shikimic acid pathway (Hull, 2001b; Broadley *et al*., 2012). Mn deficiency in plants is very difficult to detect with leaf chlorsis being the main indicator (which is also an indicator for several other nutrient deficiencies). Plants that are limiting in Mn are also more susceptible to stresses such as freezing temperatures and fungal diseases (Broadley *et al*., 2012).

Mn can exist in six different oxidative states, but is typically found in an insoluble state in soils and must be converted to Mn^{+2} before being taken up by plant roots (Broadley *et al*., 2012). Conversion to a soluble state is highly dependent upon the presence of organic matter and microbes in the soil, which provide a reducing power. Acidic soils provide a greater chance of solubility; however, if concentrations are too high, Mn may become toxic to plants. In alkaline soils with low organic matter content, low Mn concentrations are common, and competition from Ca^{+2} and Mg^{+2} reduce the ability of Mn^{+2} to bind to cation exchange sites in root cell walls (Hull, 2001b).

2.1.9 Copper

Cu plays a very important role in plant growth and cellular processes and is a constituent of more than 100 proteins found in plants (Broadley *et al*., 2012). It is the main atom in plastocyanin, which is required in the photosynthetic electron transport chain. Cu is also the main component of several enzymes, including: cytochrome oxidase, which catalyzes the transfer of electrons to O_2 in the respiratory electron transport chain; superoxide dismutase, which catalyzes the detoxification of superoxide radicals in chloroplasts, mitochondria and the cytosol of leaf cells; and polyphenol oxidases, which are important enzymes required for the formation of lignin and alkaloids. When Cu levels in plant cells are low, carbohydrate levels and lignin synthesis decreases, pollen production and development is reduced, photosynthesis and carbohydrate synthesis rates drop, and membrane lipids in chloroplasts become saturated, which affects the plant's ability to tolerate high light and low temperatures (Hull, 2002a; Broadley *et al*., 2012).

Cu deficiency is more common in alkaline soils and soils high in organic matter because Cu forms weakly soluble salts with carbonate or hydroxide and binds to organic substances (Hull, 2002b; Broadley *et al*., 2012). The most abundant form of Cu is the oxidized ion, Cu^{+2}; however, it binds strongly to clay and organic cation exchange groups, rendering it unavailable. The reduced form, Cu^{+} is less abundant, primarily existing in wet soils (Hull, 2002b). High soil N concentrations can also cause low Cu availability (Broadley *et al*., 2012).

2.1.10 Zinc

Zn is the third most abundant metallic micronutrient; however, like Mn, Zn deficiency can be difficult to detect. The uses of Zn in plant cell tissues are not as well known as other nutrients, but it is understood that it plays an important role alongside Cu in the detoxification of superoxide radicals as a component of the enzyme CuZn superoxide dismutase; it is involved in the translation process of mRNA reading by ribosomes as a constituent of RNA and DNA polymerase; and it affects protein synthesis by reducing the length of ribosomes when Zn is deficient (Hull, 2001a; Broadley *et al*., 2012). Additionally, low concentrations of Zn can result in the loss of important solutes, such as sugars, acids, and nutrient ions from cells due to leaky cell membranes (Hull, 2001a).

In the soil solution, Zn typically exists as a divalent cation (Zn^{+2}) and is more available in acidic to neutral pH levels (Hull, 2001a). In alkaline conditions, Zn^{+2} binds to clay particles and calcium carbonate, rendering it less available for plant uptake; however, in these soils, Zn can also be taken up as $ZnOH^{+}$. High P levels in the soil also reduce Zn availability due to the formation of precipitates (Hull, 2001a; Broadley *et al*., 2012).

2.2 Soil Chemical and Physical Factors Affecting Nutrient Availability

Even when nutrients are present in the soil, they are not necessarily biologically available for uptake by tree roots. In order to be absorbed by roots, the nutrients must be in their ionic form, and must make their way toward the root surface. Movement of ions in the soil can occur through mass water flow (transported along a water potential gradient driven by transpiration), diffusion along a concentration gradient, or root interception (Roberts *et al*., 2006). Several factors can affect the bioavailability of nutrients including: soil texture, soil compaction, bulk density, soil moisture, soil temperature, organic matter, and soil pH.

2.2.1 Soil Texture

The composition of urban soils can range greatly across a city and even a particular location. There are three main types of soil particles characterized by their size: sand (2.0-0.02 mm), silt (0.02-0.002 mm), and clay (<0.002 mm) (Fitzpatrick *et al*., 1999; Roberts *et al*., 2006). The suitability of an urban soil for tree growth depends on the structure of the soil and the pore spaces between particles. For example, when compacted, the pore spaces between clay particles can become very small, inhibiting root penetration, water infiltration, and oxygen availability. On the other hand, due to their small particle size and therefore, larger surface area, clay soils have a high capacity for storing water and adsorbing nutrients (Roberts *et al*., 2006; Hawver and

Bassuk, 2007). Clay soils have a high cation exchange capacity (CEC), which is a measure of the nutrient-holding ability of a substrate (Craul, 1999). Sandy soils have a poor capacity for storing nutrients due to large pore spaces that allow for very rapid water infiltration that wash away many of the nutrients. An ideal soil for nutrient availability and plant growth is one that maintains a balance between water-holding capacity and aeration (Trowbridge and Bassuk, 2004; Roberts *et al*., 2006).

2.2.2 Soil Compaction

Soil compaction is a measure of soil strength or force, typically expressed in Pascals (Pa) (Roberts *et al*., 2006). The degree of compaction of a given soil is dependent on soil texture, moisture content at the time of applied force, organic matter content, and pore space (Craul, 1992). When soils are compacted, the capacity of the soil to retain moisture is limited, macropore space necessary for oxygen and aeration is reduced, and the mechanical resistance for root penetration is increased (Watson and Kelsey, 2006). When the soil strength exceeds 2000 to 2500 kPa, root growth begins to stop, and at compaction values as low as 700 kPa, the penetration of roots into the soil is reduced by half (Roberts *et al*., 2006). This has implications for nutrient absorption since roots may be restricted in their ability to move freely within the soil and reach available nutrients in different compacted horizons. Additionally, low oxygen levels create a reducing environment in the soil that affects the ionic composition of nutrients and their solubility; this effect is typically negative, but ultimately depends on the chemical properties of the nutrient. Common urban trees in southern Ontario, silver maple (*Acer saccharinum*) and northern red oak are intermediate in their resistance to soil compaction; whereas, sugar maple, white ash, and American mountain ash (*Sorbus americana*) are susceptible (Craul, 1992).

2.2.3 Bulk Density

Bulk density is a common measurement of compaction and can be defined as the mass of dry soil per unit of bulk volume, including air spaces (Rivenshield and Bassuk, 2007). Clay soils typically have a bulk density range of 1.0 to 1.6 Mg/m^3, and sandy soils are typically in the range of 1.2 to 1.8 Mg/m^3 (Aubertin and Kardos, 1965). Craul and Klein (1980) reported a range of bulk densities in Syracuse, New York from 1.54 to 1.90 Mg/m^3, and Rivenshield and Bassuk (2007) noted that many compacted urban soils typically have a bulk density in the range of 1.6 to 2.0 Mg/m^3. High bulk density impacts nutrient availability by reducing water infiltration and restricting root growth. Water provides a medium for nutrients to be present in their soluble, bioavailable state(s), and restricting the growth of roots limits the area in which fine roots can absorb nutrients (Roberts *et al*., 2006). An ideal soil with 50 percent pore space has a bulk density of 1.33 Mg/m^3 (Craul, 1992). Root restriction typically occurs between bulk densities of 1.4 Mg/m^3 in clay soils and 1.6 Mg/m^3 in sandy soils, depending on the type of tree species (Aubertin and Kardos, 1965).

2.2.4 Soil Moisture

Soil moisture is an important factor affecting nutrient uptake. Moisture in the soil provides a means for ions to be transported to the root surface and absorbed by the tree. A study by Schoenau *et al.* (1993) found that the amount of N, P, K, and S available in the soil for plant uptake decreased significantly as soil moisture content decreased. This can be attributed to the fact that as the soil becomes drier, the diffusion path for ions to travel becomes longer and there is less soil solution between soil pores. The type of soil and the level of compaction are two main factors that can affect soil moisture content. Excess moisture due to poor drainage and aeration can cause root decay, lack of oxygen diffusion into the soil, and eventually plant death

(Trowbridge and Bassuk, 2004). In addition to reduced nutrient diffusive flux, insufficient moisture can lead to increased soil strength and lack of water availability, causing restriction of root growth (Day *et al*., 2010). If water infiltration into the soil is slow, surface runoff can occur which may remove (erode) nutrients found close to the soil surface (Roberts *et al*., 2006). Although most commonly planted urban trees prefer well-drained, moist soils, many can grow in drier areas, such as silver maple, sugar maple, northern catalpa (*Catalpa speciosa*), and northern red oak (Nesom, 2003a; Nesom, 2003b; Geyer and Broyles, 2006; Geyer *et al*., 2010).

2.2.5 Soil Temperature

The temperature of the soil affects ion diffusion – at lower soil temperatures, ion diffusion is slower and therefore, nutrient movement and uptake by trees is reduced (Craul, 1992; Western Ag Innovations, 2011a). In addition, temperature affects microbial activity, which can increase or decrease competition between the roots and microbes for nutrients depending on the microbes' optimal growing temperature. Also, the immobilization and mineralization of nutrients is affected due to the breakdown of nutrients by microbes (Herms *et al*., 2001). Like most other soil characteristics, different tree species have optimal soil temperature levels suitable for growth. Lyr and Hoffman (1967) reported that optimal growing conditions for most temperate tree species ranged from 2°C to 25°C. In urban environments across southern Ontario, the heat island effect can cause soil temperatures to regularly exceed 30°C in the summer months due to the absorption of heat by asphalt, concrete, and other impervious surfaces that dominate the landscape. Such high temperatures act to accelerate soil moisture evaporation and can have detrimental effects on the physiology and growth of roots (Graves, 1987; Roberts *et al*., 2006).

2.2.6 Organic Matter

Organic matter consists of living tissue, including leaves, branches, wood, grass, and animal remains that are comprised of lignin, cellulose, sugars, starches, fats, and waxes (Craul, 1992). Decomposition of these substrates is highly dependent on the presence of soil microbes, earthworms, and soil invertebrates, which provide most of the N and P and some of the S found in soils (Craul, 1992; Herms *et al*., 2001). Organic matter (mainly humus) has a strong cation exchange capacity like clay, which allows for positively charged nutrients to be stored, protected against leaching, and made more available for root absorption (Craul, 1992; Saebo and Ferrini, 2006). Humus is formed overtime within the topsoil as a result of the accumulation of complex organic compounds that cannot be further decomposed (Roberts *et al*., 2006). Greater humus content generally results in a more alkaline soil. If the organic matter is in the initial stages of decomposition, a more acidic soil is created due to the release of organic acids (Craul, 1992). Other benefits of organic matter include, increasing the water-holding capacity of soils, enhancing the structure of the soil, and improving aeration (Craul, 1999; Herms *et al*., 2001; Roberts *et al*., 2006). Lack of organic matter can make soil more vulnerable to increased compaction and elevated bulk density since the structure of the soil is more easily altered and its macropore space is reduced (Rivenshield and Bassuk, 2007).

2.2.7 Soil pH

The pH of the soil is another important factor that affects nutrient availability and root growth (Figure 2.1). For example, in very acidic conditions, P is relatively insoluble and Ca and Mg can become deficient (Roberts *et al*., 2006). In alkaline soils, B, Cu, Fe, Mn, and Zn are often found in very low concentrations because they exist in insoluble forms that are not available for plant uptake (Day *et al*., 2010). These nutrients reach maximum solubility at a pH of 5.0 to 5.5, and decrease considerably at pH levels greater than 7.5 (Craul, 1992). In terms of N uptake, a lower pH favours the uptake of NO_3^- and a higher pH favours the uptake of NH_4^+ (White, 2012). Most nutrients are available at neutral to slightly acidic conditions (6.0 to 7.0), which is where root growth is also generally favoured (Craul, 1992). For most commonly planted urban trees, soil pH preference typically ranges from acidic to slightly basic (Roberts *et al*., 2006). For example, silver maple has a pH tolerance of 4 to 7.3; northern red oak has a tolerance of 4.3 to 7.3; American mountain ash has a tolerance of 5.3 to 6.8; and white ash has a tolerance of 4.7 to 7.5 (USDA, 2012a,b,c,d).

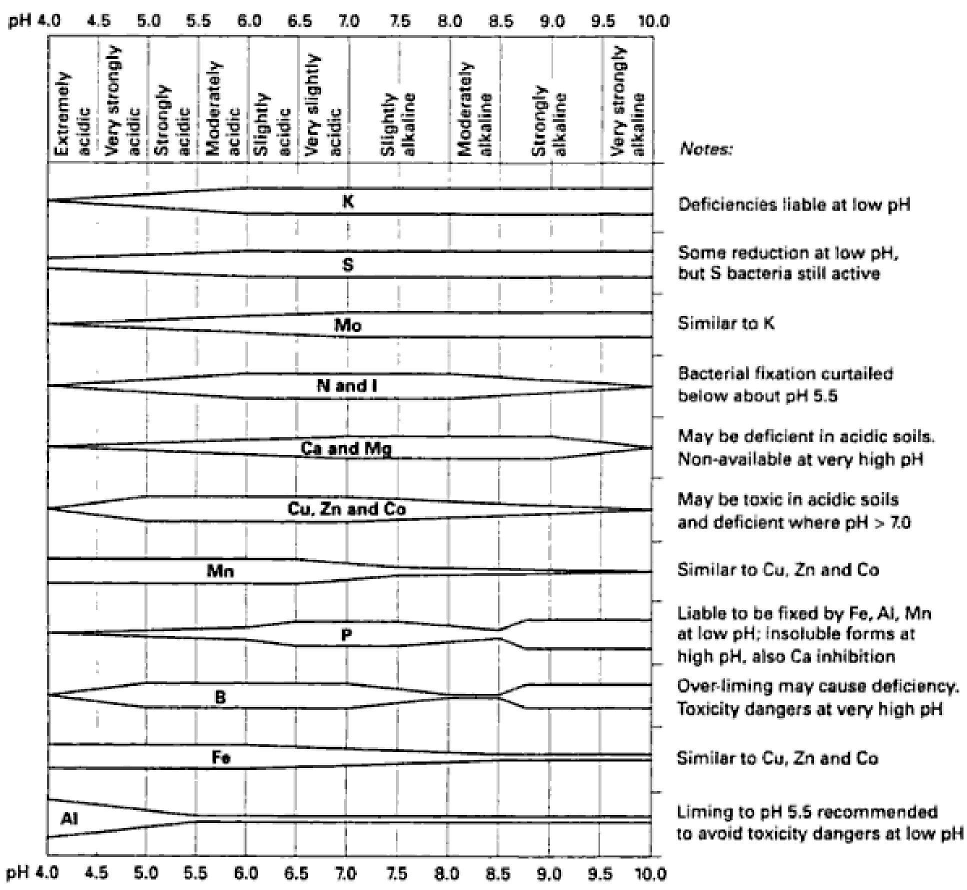


Figure 2.1: Influence of soil pH on the availability of nutrient elements in organic soils. The width of the bands indicates the degree of nutrient availability to plant roots (Roberts *et al*., 2006).

2.3 PRS^{TM}-Probes

Plant Root Simulator (PRS)^{TM}-probes are ion exchange resins that provide an alternative means to measure nutrient concentrations in the soil. Unlike conventional chemical extraction methods, these probes measure the bioavailable nutrients in the soil rather than the total nutrient pool, providing a more accurate representation of the nutrients absorbed by plant roots (Western Ag Innovations, 2011a). Most conventional chemical methods for soil nutrient analysis are static and do not account for the movement of ions in the soil. They also cannot distinguish between forms of nutrients that are biologically available and those that are unavailable for plant uptake (Qian and Schoenau, 2002). To overcome this issue, PRS^{TM}-probes act as ion exchange membranes and adsorb anions and cations in the soil very similar to what occurs on a plant root surface. This provides a representation of the overall nutrient supply rate since charged ionic species are continuously adsorbed over the burial time of the PRS^{TM}-probe (Greer *et al*., 2003).

The nutrient supply rate obtained from PRS^{TM}-probes is expressed as the weight of nutrient adsorbed per surface area of ion-exchange membrane over time (µg nutrient/10cm^2 ion-exchange membrane surface area/time of burial). The supply rate cannot be directly compared to concentrations obtained from conventional extraction methods due to the dissimilarity in the units of measurement (Western Ag Innovations, 2011a). However, several studies have shown that ion exchange resins are well correlated with conventional methods and tissue analysis for assessing plant nutrient uptake (Schoenau *et al*., 1993; Greer and Schoenau, 1994; Tejowulan *et al*., 1994; Qian and Schoenau, 1995; Hope, 2007). Although the number values reported cannot be directly compared, these studies have reported positive linear trends with conventional methods of assessment. Furthermore, conducting tissue analysis allows for additional confirmation that PRS^{TM}-Probes are able to accurately distinguish between nutrients that are bioavailable and those that are not available for plant absorption, unlike most conventional methods (supplementary information about the PRS^{TM}-probes can be found in Appendix F).

Two types of PRS^{TM}-probes are available: one that measures cations (positively charged ions) and one that measures anions (negatively charged ions). The membranes of the probes are saturated with permanently charged functional groups that attract oppositely charged ions (bicarbonate, HCO_3^-, for anion-exchange probes and sodium, Na^+, for cation-exchange probes). These charged functional groups are neutralized by counter-ions that are exchangeable with other ions in the soil (Schoenau *et al*., 1993). After removal from the soil, the probes must be thoroughly washed with deionized water to remove all remaining soil particles. Once clean, they are eluted with 0.5 M HCl for 1 hour and then analyzed for nutrient concentrations using automated colorimetry and inductively-coupled plasma spectrometry (ICP) (Hangs *et al*., 2002). The data collected from the probes can be used to extract meaningful soil nutrient conclusions since many of the processes that affect nutrient uptake by roots also affect the adsorption of nutrients to the PRS^{TM}-probes (Western Ag Innovations, 2011b).

PRS^{TM}-probes have been used in a variety of scientific fields, including agriculture, forestry, ecology, horticulture, and environmental (Western Ag Innovations, 2011a). Koehn *et al*. (2002) used PRS^{TM} anion exchange membranes to measure NO_3^- in the topsoils of four apple orchards with various management practices over the growing season. The authors found that the NO_3^- adsorbed to the probes was consistent with what was expected under various orchard management practices. They also found that the sequential use of PRS^{TM}-probes provided valuable information about temporal changes in the supply of NO_3^- in the soil overtime. Hope (2007) used PRS^{TM}-probes to determine the response in NO_3^- and NH_4^+ supply rates after a clearcut harvest compared to a forested area in British Columbia. The author used a conventional method in one study site and the PRS^{TM}-probes in the other, and found that the response in nutrient concentrations after harvesting followed similar trends for both methods over a three-year period. Other studies have used PRS^{TM}-probes to determine fertilizer requirements for different plants, such as cereals, oil seed, and forage crops. The use of PRS^{TM}-probes and other resin membranes are becoming increasingly popular since the same factors that affect the absorption of nutrients by tree roots also affect the absorption of ions to the PRS^{TM}-Probes. These factors include: soil moisture, soil temperature, ion diffusion, mineralization and immobilization, and dissolution (Qian and Schoenau, 2002).

2.4 Tree Roots

Tree roots are essential for obtaining nutrients, water, and oxygen from the soil and for providing stability for the tree. When a tree is first planted, its root ball is typically 0.5 to 0.6 m in radius. The first two to five years after planting are crucial for achieving tree establishment and ensuring the roots can obtain enough water and nutrients to grow past the root ball and extend into the surrounding soil (Consolloy, 2007; Irvine, personal communication). Once a tree becomes established and matures, its roots can extend several times past the canopy drip line, which is the tree's projected crown area (Craul, 1999; Roberts *et al*., 2006). In some cases, roots can extend four to seven times greater than the canopy depending on the level of restriction in the soil. In terms of vertical movement, most roots (up to 80 percent) exist in the top 30 cm of the soil and typically do not extend deeper than 1 m (Craul, 1992; Hawver and Bassuk, 2007). In urban areas, fine roots that are responsible for the majority of nutrient and water absorption can be found within the top 10 cm of the soil surface where resources are most plentiful. These roots are most susceptible to fluctuating soil temperatures, compaction resulting from vehicular and pedestrian traffic, and variable moisture and nutrient availability (Craul, 1999; Watson and Kelsey, 2006).

2.5 Mulch

Mulching around plants, and especially trees, dates back hundreds of years (Roberts *et al*., 2006). Currently, various types of organic and inorganic mulches are widely applied in the landscape. Inorganic mulches mainly consist of crushed stone, pebbles, gravel, rubber, polyethylene film, or aluminum foil, while organic mulches are typically composed of wood chips, leaves, bark, pine needles, lawn clippings, straw, or peat moss (Duryea *at al*., 1999; Harris *et al*., 1999; Herms *et al*., 2001).

2.5.1 Benefits of Organic Mulch

Application of organic mulch to the soil surface covering the rooting zone of newly planted and mature urban trees can dramatically improve their survival and long-term health (Litzow and Pellett, 1983; Green and Watson, 1989). Organic mulches improve urban soil conditions by supplying nutrients, increasing soil moisture retention, increasing organic matter content, controlling surface temperature fluctuations, reducing soil compaction, and suppressing weeds (Lal, 1974; Watson, 1988; Duryea *et al*., 1999; Iles and Dosmann, 1999; Rivenshield and Bassuk, 2007). Even though the application of mulch provides many benefits to the soil, some of the positive attributes, such as supplying nutrients and reducing soil compaction, occur more gradually overtime (i.e., over years and not months) (Hawver and Bassuk, 2007).

One of the most frequently cited advantages of organic mulch is its ability to improve moisture retention in soils. Watson (1988) compared tree root density and soil moisture content in trees surrounded by turfgrass and trees that were treated with organic mulch. The results indicated that the application of organic mulch increased soil root density and improved soil moisture content compared to trees surrounded by turfgrass. Turfgrass-treated plots were thought to have less favourable soil moisture and tree root density because of competition with grass for rooting space, for nutrients, and for available water. Russell (1939) also reported that applying 4 cm (1.5”) of straw mulch to the surface of soils improved soil moisture content by restricting evaporation. One reason for this is because mulch acts as a protective barrier between the soil and the air, thereby buffering fluctuating air temperatures. This mulch barrier prevents excessive water evaporation from the soil surface on hot, dry days because the soil is kept at a cooler temperature (Herms *et al*., 2001). Lal (1974) reported soil temperature differences as much as 8°C between mulched and un-mulched plots at a depth of 5 cm. Similar findings were made by Li (2011), who observed soil temperatures at a depth of 10 cm as high as 28°C in un-mulched areas compared to temperatures ranging from 20 to 24°C in mulched areas.

Increased nutrient availability through the decomposition of organic matter is another important attribute of mulch application (Craul, 1999). Depending on the type of mulch, various nutrients, such as N, P, K, S, Mg, and Ca, may be present in the parent material that can be released into the soil during decomposition (Craul, 1992; Duryea *et al*., 1999). Furthermore, improvements to soil bulk density have been documented in laboratory settings. Rivenshield and Bassuk (2007) conducted a laboratory experiment to determine the percentage of sphagnum peat mulch and food waste compost (by volume) required to reduce bulk density to below root-restricting levels in both sandy and clay soils. The authors saw improvements over the course of several days and reported that at least 33 percent organic amendment was required for sandy loam soils and at least 50 percent for clay loam soils. However, this study was conducted over a short time-span and only measured soil samples to a depth of 10 cm. In field experiments, changes in soil compaction and bulk density (greater than 10 cm in depth) have been shown to take several years to decades to recover from heavily degraded conditions (Froehlich *et al*., 1985). It is, therefore, important to recognize that improvements to bulk density and soil compaction through the use of organic mulch may occur more gradually over-time in natural settings compared to the results reported by Rivenshield and Bassuk (2007).

2.5.2 Effects of Mulch on Nutrient Availability

Decomposition rate, carbon and lignin content, and nutrient release are important characteristics that should be taken into account when choosing a particular organic mulch (Duryea *et al*., 1999). In general, mulches such as hardwood bark, wood chips, pine, cypress, sawdust, and straw that have high ratios of lignin to nitrogen (lignin:N) and carbon to nitrogen (C:N) can result in initial soil N deficiency. High C:N ratios (greater than 30:1) typically support increased microbial growth due to the high carbon content in the material, which is their primary energy source. This can lead to reduced N availability in the soil for tree roots due to competition from microbes (Herms *et al*., 2001). Some mulches with high C:N ratios have slower decomposition rates because they are more recalcitrant and harder to breakdown by microorganisms, so N deficiency may be more gradual (Meentemeyer, 1978). On the other hand, sawdust and straw decompose quickly and can cause a rapid increase in microbial activity (Harris *et al*., 1999). Yard wastes also decompose quickly and provide an initial surge of nutrients into the soil; however, it is important to note that they must be reapplied more frequently, are often very heterogeneous, and have a higher probability of containing allelopathic properties and weed seeds (Duryea *et al*., 1999). Additionally, lawn clippings and leaves can impede soil water infiltration and soil oxygen availability because they clump together forming an impermeable layer on the surface (Harris *et al*., 1999). Table 2.1 provides the general C:N ratios of several types of mulches; however, it is important to note that the wood chips reported have a very high C:N ratio, which is not necessarily true in all cases.

Table 2.1. Mulch materials and their C:N ratios (adopted from Craul, 1992)

Mulch Material	C:N Ratio
Hay	19:1
Manure	25:1
Leaves	40:1
Hardwood bark	115:1 – 435:1
Straw	128:1 – 150:1
Softwood Bark	131:1 – 930:1
Sawdust	200:1 – 500:1
Wood chips	615:1

Herms *et al*. (2001) recommends the use of partially decomposed mulches because the C:N ratio in these mulches is lower, allowing for greater N availability for the tree. One of the most popular types of organic mulch that is often recommended in city planting details is wood chips (City of Toronto, 2002; Irvine, personal communication). Wood chips do have a high C:N ratio, however, once the mulch begins to decompose and the microbes die, the N is released into the soil and the effect of N depletion is reduced over time (Scharenbroch and Lloyd, 2006). Wood chips produced from branches and fallen trees rather than from pure wood typically have lower C:N ratios, increasing the N availability (Herms *et al*., 2001).

2.5.3 Mulch Application

There has been much discussion in the scientific community regarding the correct methods to apply mulch around trees. First of all, piling mulch into a “volcano” around the base of the tree can cause transmission of diseases and decay of the bark; therefore, it is recommended that mulch be applied more than 15 cm from the trunk (Koski and Jacobi, 2004). Furthermore, the thickness of mulch applied to the rooting zone can have an impact on tree survival and growth.

Excessive mulch can reduce water infiltration and oxygen availability, suffocating the tree (Billeaud and Zajicek, 1989; Roberts *et al*., 2006). Arnold *et al*. (2005) suggested applying a layer no thicker than what is required to suppress weeds. Gouin (1984) specified that organic mulch should be applied to a maximum depth of 7.5 cm (3”); however, more recent documents state the optimal depth is between 10-15 cm (4 to 6”) (Harris *et al*., 1999; Roberts *et al*., 2006). On the other hand, Watson and Kupkowski (1991) reported no negative effects to soil moisture, temperature, and oxygen diffusion rates when wood chips were applied to a depth of 0.45 m (18”) over tree roots in a playground. The authors caution that different mulch types will yield different results at greater depths. Additionally, tree planting depth and improper location of mulch application may cause detrimental effects on tree growth and survival. Gilman and Grabosky (2004) reported that mulch applied over the root ball of new deeply planted coastal live oak trees (*Quercus virginiana* P. Mill.) actually reduced water availability and increased tree stress. However, after three months, the trees no longer exhibited signs of stress even in dry weather conditions.

In terms of the areal coverage of mulch, very little research has been conducted to determine the optimal area that should be covered. Watson and Himelick (1997) suggested applying enough mulch to cover the area of root growth that would occur during the first years of tree establishment. For a tree with a diameter of 8 cm, a mulch radius of 1-1.5 m would be ideal. Li (2011) found that wood chips applied with a 1.5 m radius to the base of newly planted trees mitigated the rise in near-surface soil temperatures more effectively than a 0.75 m or 1.0 m radius. In North America, the typical industry standard for mulch application is a radius of 0.75 m and the general government recommendation is 1 m (Irvine, personal communication). Both the City of Waterloo and the City of Toronto state in their planting standards that mulch should be applied to a depth of 10 cm; however, there are no specific requirements for mulch areal coverage (City of Waterloo, 2001; City of Toronto, 2002). As mentioned previously, most mature root systems extend several metres past the canopy drip line of a tree. A larger diameter of mulch can assist in creating more favourable growing conditions for roots just outside the root ball for both mature and newly planted trees; however, this information is rarely taken into account in practice when determining optimal mulch application.

2.6 Summary

Despite recognition of the positive aspects of applying mulch as a soil amendment, there are still gaps that must be addressed in order to maximize the benefits to urban trees. Research has been conducted on the differences between various mulch types (inorganic and organic) in order to determine their properties, the benefits and potential disadvantages of mulch, and the depth of mulch application. However, little research has been carried out focusing on the areal coverage of mulch application in degraded urban soils. It is generally understood in the scientific community that applying a greater area of mulch around the base of a tree will provide more benefits. Nevertheless, no studies have examined how various extents of mulch application (to the edge of the canopy drip line, past the drip line, and so on) impact the physical and chemical characteristics of soil. Additionally, although PRS™-probes have been used in a variety of scientific studies, no research has been conducted on their effectiveness in determining nutrient supply rates in urban soils or under different mulch treatments (Greer, personal communication). Therefore, further investigation in this area of research is warranted to determine how to use this technology (PRS™-probes) as a method for investigating nutrient availability in urban soil, especially for the purpose of optimizing amendment application (such as organic mulch) in order to maximize soil nutrient availability for urban trees.

CHAPTER 3

3.1 Abstract

Trees planted along city streets and in urban parks are subject to many adversities that affect growth and can often result in mortality; these include poor moisture availability, fluctuating surface temperatures, soil compaction, inadequate nutrient supply, and little organic matter. The application of organic mulch to the rooting medium of newly planted urban trees has the potential to improve the soil chemical and physical properties necessary for tree root health. This study examined the difference in soil nutrient supply rates (μg/10cm^2/28 days) between three areal treatments of wood chips (0.75m, 1.0m and 1.5m radii) and before mulch application versus after mulch application using Analysis of Covariance. PRS^{TM}-Probes were inserted into the soil over six 28-day periods to measure the supply rate of bioavailable nutrients (NO_3^-, NH_4^+, P, K, S, Ca, Mg, and Cu). Meteorological data and other soil chemical and physical factors were measured and included as covariates in the statistical model to determine if they had a significant impact on nutrient supply rate. Results indicate that mulching had a significant effect ($p<0.05$) on P; supply rates were lower in the reference plots compared to the treatment plots post-mulching. S, Ca, Mg, and Cu supply rates decreased after mulch application; however, the decrease was observed in all treatments and the reference plots, which is likely due to temporal variations in plant demand rather than mulching. The wood chips also had a significant impact on buffering fluctuating soil temperatures and reducing soil moisture loss compared to non-mulched plots. The knowledge obtained from this research can be used to improve urban forest management strategies by providing a more in-depth understanding of the prescriptive use of organic mulch for improving soil conditions necessary for the long-term health and survival of urban trees.

3.2 Introduction

Trees are an integral part of the urban environment and play an important role in defining the city landscape. Within populated areas, trees are referred to as the "urban forest", which includes "trees along city streets, in parks, ravines and natural areas, front and backyards of homes, and in landscaped open spaces" (City of Toronto, 2010). Several beneficial attributes of trees growing in urban areas include: improved air quality (serving as a sink for carbon dioxide and other greenhouse gases), moderation of air temperature and associated mitigation of the urban heat-island effect (through evapo-transpiration and shading), soil erosion control, reduction of storm water run-off (water retention in the rooting zone), provision of wildlife habitat, beautification of parks and recreational spaces, and aesthetic enhancement of private property (Trowbridge and Bassuk, 2004; Roberts *et al*., 2006; Millward and Sabir, 2010). Despite recognition of the value of trees in the cityscape, most urban areas have failed to provide the necessary soil conditions for trees to grow to maturity—nullifying the potential to fully realize their ecological and aesthetic benefits (Millward and Sabir, 2010).

The soil supporting the urban forest in densely built cities is frequently compromised by shallow soil depth, heavy compaction from vehicular and pedestrian traffic, and impervious surfaces. These factors significantly impact the growth of roots and the stability of the tree, with the latter two also limiting soil water infiltration due to reduced porosity leading to increased plant moisture stress. High temperatures, inadequate organic content, poor nutrient availability, and contamination from air, construction, and motor vehicle pollutants are additional concerns for urban trees. These factors alter the chemical and physical properties of soil, which negatively impact the growing conditions for trees (Craul, 1999; Trowbridge and Bassuk, 2004; Day *et al*., 2010).

Tree roots are essential for obtaining nutrients, water, and oxygen from the soil and for providing stability for the tree. When a tree is first planted, its root ball is typically 0.5 to 0.6 m in radius. The first two to five years after planting are crucial for achieving tree establishment and ensuring the roots can obtain enough water and nutrients to grow past the root ball and extend into the surrounding soil (Consolloy, 2007; Irvine, personal communication). Once a tree becomes established and matures, its roots can extend several times past the canopy drip line, where the drip line is the tree's projected crown area (Craul, 1999; Roberts *et al*., 2006). In some cases, root length can extend four to seven times greater than the canopy depending on the level of restriction in the soil. In terms of vertical movement, most roots exist in the top 30 cm of the soil and typically do not extend deeper than 1 m (Hawver and Bassuk, 2007). In urban areas, fine roots that are responsible for the majority of nutrient and water absorption can be found within 10 cm of the soil surface where resources are most plentiful. These roots are most susceptible to fluctuating soil temperatures, compaction resulting from vehicular and pedestrian traffic, and variable moisture and nutrient availability (Craul, 1999; Watson and Kelsey, 2006).

Trees growing in urban parks provide an opportunity for cities to expand their total canopy cover and establish improved growing conditions for newly planted trees. City parks often cover large contiguous downtown areas and have the necessary characteristics, such as sufficient soil volume and quality, for roots to expand and flourish (Trowbridge and Bassuk, 2004). Conversely, streetscape trees are confined to small pockets of soil and are restricted in growth by overhead utility wires and the surrounding impervious surfaces. Therefore, developing strategies to further improve the soil conditions in urban parklands offers a viable means for cities to promote the continued growth of mature trees and ensure those that are newly planted can reach the same health and longevity (Millward and Sabir, 2010).

Application of organic mulch to the soil surface covering the rooting zone of newly planted and mature urban trees can dramatically improve their survival and long-term health (Litzow and Pellett, 1983; Green and Watson, 1989). Organic mulches improve urban soil conditions by supplying nutrients, improving soil moisture retention, increasing organic matter content, controlling surface temperature fluctuations, reducing soil compaction and bulk density, and suppressing weeds (Russel, 1939; Lal, 1974; Watson, 1988; Billeaud and Zajicek, 1989; Duryea *et al*., 1999; Iles and Dosmann, 1999; Rivenshield and Bassuk, 2007). Increased nutrient availability through the decomposition of organic matter is an important attribute of mulch application around urban trees (Craul, 1999). Depending on the type of mulch, various nutrients, such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S) magnesium (Mg), and calcium (Ca), may be present in the parent material that can be released into the soil during decomposition (Craul, 1992; Duryea *et al*., 1999). Reducing bulk density and soil compaction improves water infiltration and enables root growth. Water provides a medium for nutrients to be present in their soluble, bioavailable state(s), and allowing the growth of roots increases the area in which fine roots can absorb nutrients (Roberts *et al*., 2006). Mulch also acts as a protective barrier between the soil and the air, thereby buffering fluctuating air temperatures. This prevents excessive water evaporation from the soil surface on hot, dry days because the soil is kept at a cooler temperature (Herms *et al*., 2001). Soil temperature differences as much as 8°C between mulched and un-mulched plots have been reported in various studies (Lal, 1974; Iles and Dosmann, 1999; Li, 2011).

Decomposition rate, carbon and lignin content, and nutrient release are important characteristics that should be taken into account when choosing a particular organic mulch (Duryea *et al*., 1999). In general, mulches such as hardwood bark, wood chips, pine, cypress, sawdust, and straw that have high ratios of lignin to nitrogen (lignin:N) and carbon to nitrogen (C:N) can result in initial soil N deficiency. High C:N ratios (greater than 30:1) typically support increased microbial growth due to the high carbon content in the material, which is their primary energy source. This leads to reduced N availability in the soil for tree roots due to competition from microbes (Herms *et al*., 2001). Some mulches with high C:N ratios have slower decomposition rates because they are more recalcitrant and harder to breakdown by microorganisms; in such cases N deficiency may be more gradual (Meentemeyer, 1978). On the other hand, sawdust and straw decompose quickly and can cause a rapid increase in microbial activity; however, they must be applied more frequently (Harris *et al*., 1999). Even though some types of mulch, like wood chips, have higher C:N ratios, once the mulch begins to decompose and the microbes die, the N is released into the soil and the effect of N depletion is reduced over time (Scharenbroch and Lloyd, 2006). Wood chip mulch produced from branches and fallen trees rather than from pure wood typically have lower C:N ratios, increasing the N availability (Herms *et al*., 2001).

One method to measure soil nutrients is through the use of Plant Root Simulator (PRS)^{TM}-probes. These probes are ion exchange resins that measure the bioavailable nutrients in the soil rather than the total nutrient pool, providing a more accurate representation of the nutrients absorbed through the plant roots (Western Ag Innovations, 2011a). Most conventional chemical methods are static and do not account for the movement of ions in the soil or distinguish between forms of nutrients that are unavailable for plant uptake (Qian and Schoenau, 2002). To overcome this issue, PRS^{TM}-probes act as ion exchange membranes and adsorb anions and cations in the soil very similar to what occurs on a plant root surface. This method of nutrient capture provides a representation of the overall nutrient supply rate since charged ionic species are continuously adsorbed over the burial time (Greer *et al*., 2003). The nutrient supply rate is expressed as the weight of nutrient adsorbed per surface area of ion-exchange membrane over time (µg nutrient/10cm^2 ion-exchange membrane surface area/time of burial). The supply rate cannot be directly compared to concentrations obtained from conventional extraction methods due to the dissimilarity in the units of measurement (Western Ag Innovations, 2011a).

There are two types of PRS^{TM}-probes: one that measures cations (positively charged ions) and one that measures anions (negatively charged ions). The membranes of the probes are saturated with permanently charged functional groups that attract oppositely charged ions in the soil (sodium, Na^+, for cation-exchange probes and bicarbonate, HCO_3^-, for anion-exchange probes) (Schoenau *et al*., 1993). After removal from the soil, the probes must be thoroughly washed with deionized water to remove all remaining soil particles. Once clean, they are eluted with 0.5 M HCl for 1 hour and then analyzed for nutrient concentrations using automated colorimetry and inductively-coupled plasma spectrometry (ICP) (Hangs *et al*., 2002).

Several studies have shown that ion exchange resins are well correlated with conventional soil nutrient analysis methods and tissue analysis for assessing plant nutrient uptake (Schoenau *et al*., 1993; Greer and Schoenau, 1994; Tejowulan *et al*., 1994; Qian and Schoenau, 1995). Although the number values cannot be directly compared, these studies have reported positive linear trends with conventional methods of assessment. Furthermore, conducting tissue analysis allows for further confirmation that PRS^{TM}-Probes are able to accurately distinguish between nutrients that are bioavailable and those that are not available for plant absorption, unlike most conventional methods (supplementary information about the PRS^{TM}-probes can be found in Appendix F). PRS^{TM}-probes have been used in a variety of scientific fields, including agriculture, forestry, ecology, horticulture, and environmental science (Koehn *et al*., 2002;

Dijkstra *et al*., 2006; Hope, 2007; Lantz *et al*., 2009; Davenport *et al*., 2012). The use of PRS^{TM}-probes and other resin membranes are becoming increasingly popular since the same factors that affect the absorption of nutrients by tree roots also affect the absorption of ions to the PRS^{TM}-Probes. These factors include: soil moisture, soil temperature, ion diffusion, mineralization and immobilization, and dissolution (Qian and Schoenau, 2002).

There has been much discussion in the scientific community regarding the correct methods to apply mulch around trees. First, piling mulch into a "volcano" around the base of the tree (an all too common practice in the landscaping industry) can cause transmission of diseases and decay of the bark; therefore, it is recommended that mulch be applied more than 15 cm from the trunk (Koski and Jacobi, 2004). Second, the thickness of mulch applied to the rooting zone can have an impact on tree survival and growth. Excessive mulch can reduce water infiltration and oxygen availability, suffocating the tree (Billeaud and Zajicek, 1989; Roberts *et al*., 2006). Arnold *et al*. (2005) suggest applying a layer no thicker than what is required to suppress weeds. Gouin (1984) specified that organic mulch should be applied to a maximum depth of 7.5 cm (3"); however, more recent studies state the optimal depth is 10-15 cm (4 to 6") (Harris *et al*., 1999; Roberts *et al*., 2006). On the other hand, Watson and Kupkowski (1991) reported no negative effects to soil moisture, temperature, and oxygen diffusion rates when wood chips were applied to a depth of 0.45 m (18") over tree roots in a playground. The authors caution that different mulch types will yield different results at greater depths.

In terms of the areal coverage of mulch, very little research has been conducted to determine the optimal area that should be covered. Watson and Himelick (1997) suggested applying enough mulch to cover the area of root growth that would occur during the first years of tree establishment. For a tree with a diameter of 8 cm, a mulch radius of 1-1.5 m would be ideal. Li

(2011) found that wood chips applied with a 1.5 m radius to the base of newly planted trees mitigated the rise in near-surface soil temperatures more effectively than a 0.75-1.0 m radius. In North America, the typical industry standard for mulch application is a radius of 0.75 m and the general government recommendation is 1 m (Irvine, personal communication). Both the City of Waterloo and the City of Toronto state in their tree planting standards that mulch should be applied to a depth of 10 cm; however, there are no specific requirements for mulch areal coverage (City of Waterloo, 2001; City of Toronto, 2002). As mentioned previously, most mature root systems extend several metres past the canopy drip line of a tree. A larger diameter of mulch can assist in creating more favourable growing conditions for roots just outside the root ball for both mature and newly planted trees; however, this information is rarely taken into account in practice when planning application.

Despite recognition of the positive aspects of applying organic mulch as a soil amendment to city trees, there are still questions that must be addressed in order to maximize the benefits of mulch application. For example, no studies have examined how various extents of mulch application (to the edge of the canopy drip line, past the drip line, and so on) impact the physical and chemical characteristics of soil in degraded urban environments. Additionally, although PRS^{TM}-probes have been used in a variety of scientific studies, no research has been conducted on their effectiveness in determining nutrient supply rates in urban soils or under different mulch treatments (Greer, personal communication). Therefore, the objectives of this study were to: (1) Measure soil physical and chemical characteristics within the study area tree rooting zones that are known to affect soil nutrient availability; (2) Assess soil nutrient availability and soil physical properties for baseline (pre-mulch) soil conditions versus post-mulch conditions; and, (3) Compare soil nutrient availability and soil physical properties between treated (mulched) and non-treated (non-mulched) tree plots and among the three treatment types (mulch radii). It was expected that the application of mulch would improve the soil conditions necessary for the growth of urban tree roots compared to non-treated plots (references), and that the largest radii of mulch (1.5 m) would provide greater soil benefits (i.e., buffer a larger volume of soil against fluctuations in temperature, provide more consistent soil moisture, and provide a greater volume of soil with favourable conditions for bioavailable nutrients). It was also hypothesized that nitrate (NO_3^-) and ammonium (NH_4^+) supply rates would initially decrease under mulched plots due to the high carbon to nitrogen ratio (C:N) of the wood chips, which typically leads to competition from microbes for available nitrogen. Such knowledge will contribute to the discipline of urban forestry by providing a more in-depth understanding of the prescriptive use of organic mulches to improve the survival and long-term health of trees in urban areas.

3.3 Methods

3.3.1 Study Site

The study site is a rectangular parcel of urban parkland located at Exhibition Place, Toronto (Figure 3.1). The site is bordered by British Columbia Road to the north, Yukon Place to the east, and Lake Shore Boulevard to the south-west. During the Canadian National Exhibition (CNE), which occurs every year for two weeks at the end of August, the site is used as an overfill parking lot. Therefore, during the period of August 19 to September 5, 2011, all research activities on the site were suspended.

Figure 3.1: Bird's eye view of the study location at Exhibition Place, Toronto (Bing Maps, 2011). The red enclosure delineates the location of trees studied.

A preliminary inspection of the site in the Fall of 2010 and the Spring of 2011 revealed signs of soil structural degradation arising from pedestrian and vehicle compaction. This parkland contains a variety of tree species of differing ages and in varying states of health. All tree species included in this study are commonly planted in urban areas and parklands across southern Ontario. Intra-species comparison of response to mulching application was regarded to be appropriate since most trees were planted within the past five years and range in current diameter from 5.3-16.9 cm (all except one are less than the average tree diameter in Toronto) (Table 3.1).

Table 3.1: The common name, scientific name, and DBH of each tree species in the study

Tree Number	Species Common Name	Species Scientific Name	DBH (cm)
1	Northern catalpa	*Catalpa speciosa*	8.5
2	Northern red oak	*Quercus rubra*	10.9
3	Swedish whitebeam	*Sorbus intermedia*	11.4
4	Northern catalpa	*Catalpa speciosa*	8.0
5	White ash	*Fraxinus americana*	10.4
6	Silver maple	*Acer saccharinum*	16.9
7	Silver maple	*Acer saccharinum*	11.0
8	Silver maple	*Acer saccharinum*	12.0
9	Silver maple	*Acer saccharinum*	12.3
10	Sugar maple	*Acer saccharum*	5.7
11	Sugar maple	*Acer saccharum*	6.0
12	Sugar maple	*Acer saccharum*	5.3
13	White ash	*Fraxinus americana*	15.1
14	America Mountain ash	*Sorbus americana*	15.5
15	Northern red oak	*Quercus rubra*	9.0

Aerial imagery from the 1960s and 1980s show that several large, mature trees were once situated on the study site, but have since died and been replaced with young trees (Figure 3.2). These historical images also indicate that the northern part of the site was used as a parking lot for several years. In the 1980s, a trailer office was also located on the property and a portion of the area designated for parking was paved with either concrete or asphalt. At present, the soil is predominately sandy clay loam (sand: 69%, silt: 16%, clay: 22%) in texture and the soil surrounding several trees in the north portion of the site contains large pieces of concrete and gravel (typical of urban soil fill). The historic use of this site has resulted in years of continuous soil compaction due to pedestrian and vehicular traffic. The conditions of this site (i.e., proximity to streets, compacted soil, high soil temperatures, insufficient moisture during dry spells, and low organic matter), resemble growing conditions experienced by many newly planted urban trees. Therefore, the results of this study may be useful as guidelines for soil amendment recommendations around trees in other urban parks.

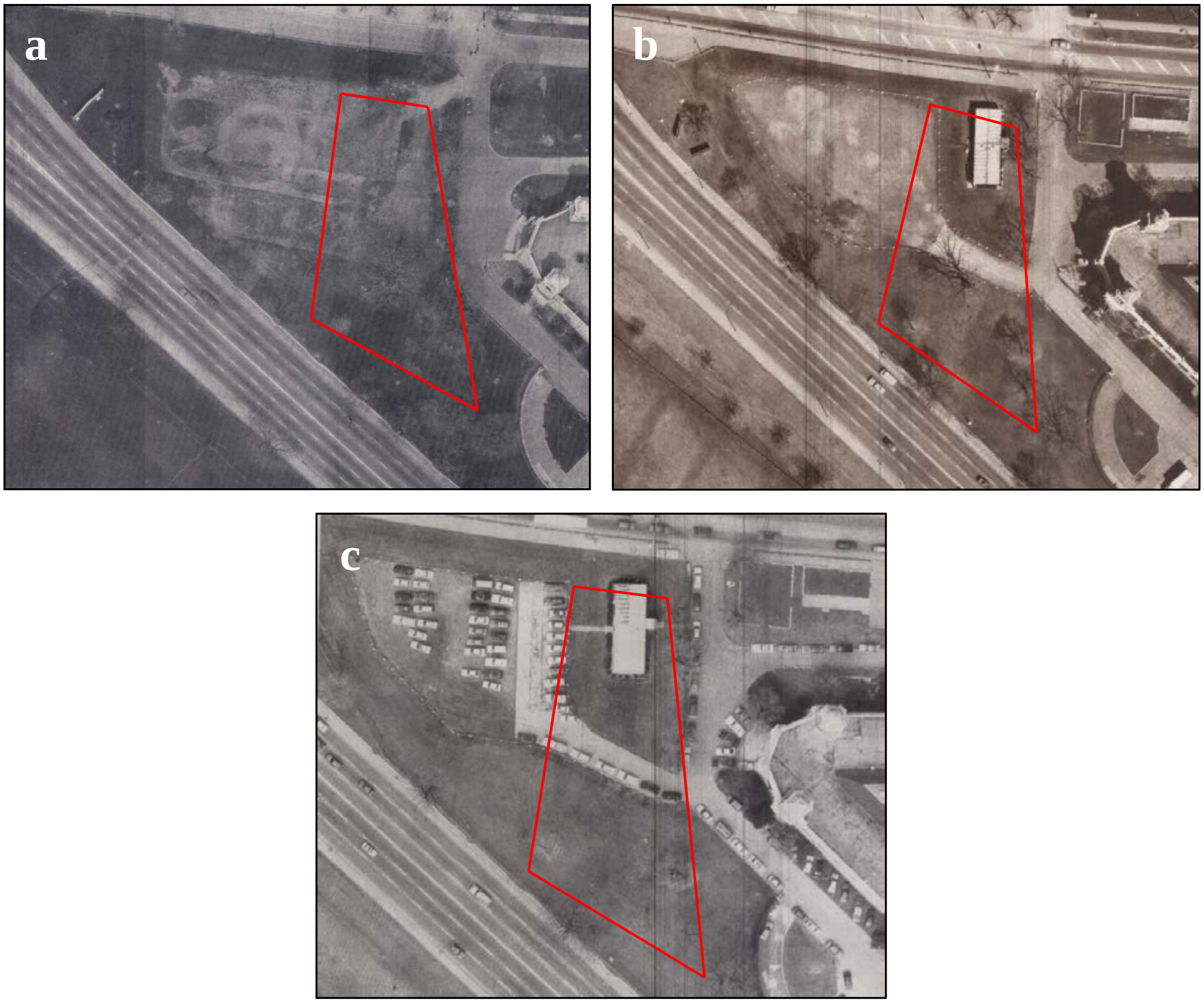


Figure 3.2: Aerial imagery of the study location in (a) 1968, (b) 1981, and (c) 1988 (Toronto Dept. of Public Works, 1968, 1981, 1988). The red enclosure delineates the present location of trees studied.

3.3.2 Experimental Design

The field experimental design consisted of three mulch treatments with three replicates of each and six references (controls) for a total of 15 plots. The treatments varied in the areal extent of mulch applied to the base of the trees (i.e., 0.75 m, 1.0 m, and 1.5 m radii covering an area of 1.77 m^2, 3.14 m^2, and 7.07 m^2, respectively). The radii of 0.75 m and 1.0 m were chosen based on the industry standard and common municipal recommendations, respectively (Irvine, personal communication). The 1.5 m radius was chosen to test if a larger areal coverage of mulch applied closer to the canopy drip line of the tree would provide additional soil physical and chemical benefits. For the purpose of this study, only the rooting zone of relatively young trees (planted fewer than five years ago) was included in order to investigate the benefits of mulch to improve the soil conditions necessary for newly planted trees to reach their full potential. Although mulch is also known to benefit mature trees, the older trees on this site are well established and their canopy size has served to create understory microsite characteristics favourable to the establishment of more resilient (with fewer fluctuations) urban soil conditions. These mature trees were, therefore, not studied.

This experiment was located at Exhibition Place so as to leverage access to existing, closely spaced, young trees that are representative of common species found in a Toronto urban park. Candidate trees growing in the northern section of the study site were excluded due to large pieces of concrete and gravel found in their surrounding soil (dissimilar from other trees on the site). The study design provides a simple and effective method of comparing mulch treatment types to each other and to the reference trees (non-mulched). In order to select which trees received which treatment, each tree was assigned a number from 1 to 15. Numbers were then drawn at random (without replacement) to assign trees to a mulch treatment. Randomization of treatment type was used to remove bias in treatment allocation. Soil nutrient analyses were conducted on three reference trees (13-15), with three additional reference trees (1, 10 and 12) used for other chemical and physical soil tests conducted as part of accompanying research projects (Figure 3.3).

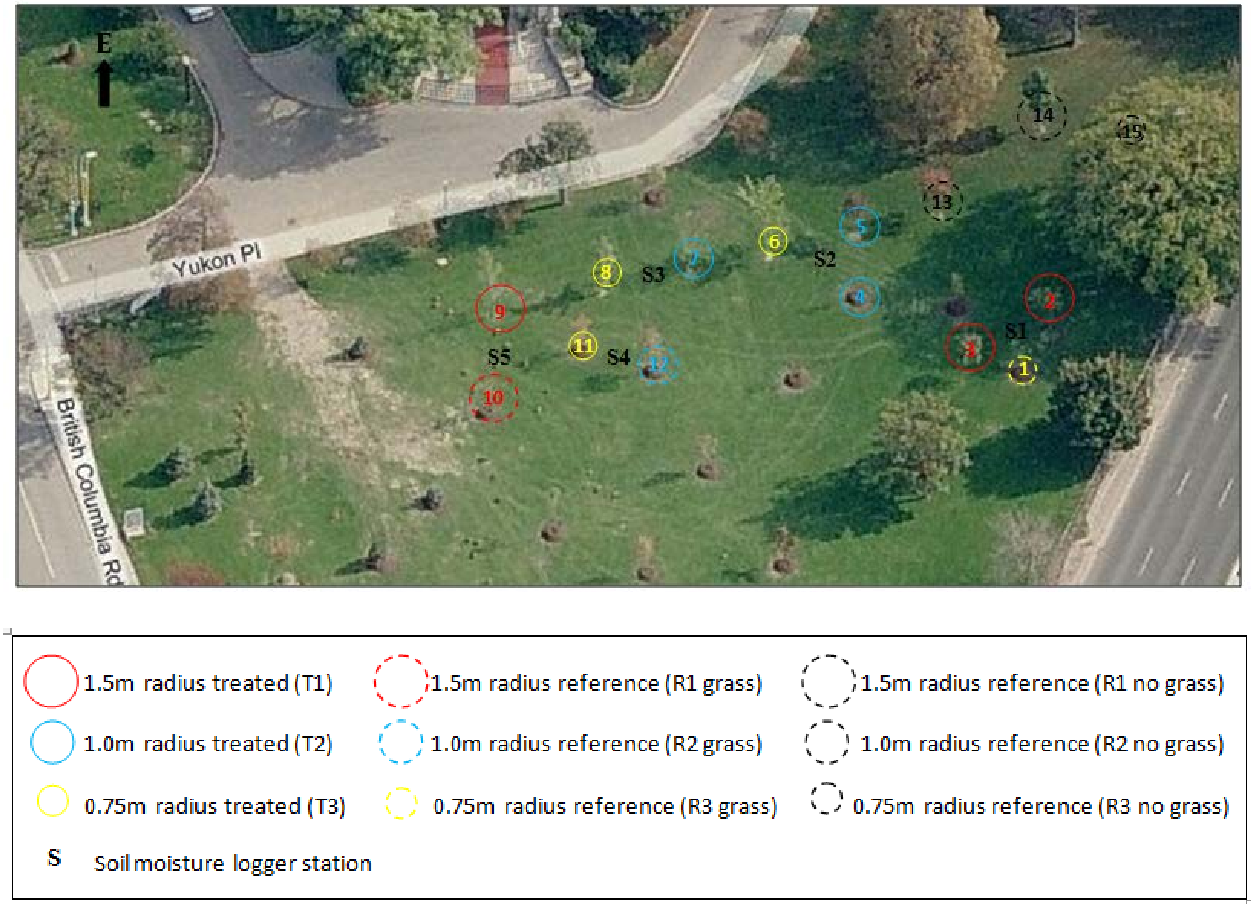


Figure 3.3: Map of mulch treatment and reference plots at Exhibition Place, Toronto (Bing Maps, 2011)

3.3.3 Mulch Type

Organic mulch composed of wood chips from recently felled Norway maple trees (green mulch) was used in this study; lab tests confirm that this mulch had a C:N ratio 123:1 (SGS Agrifood Laboratories). Mulch was delivered to the study site at the end of June, 2011 by Bruce Tree Expert Company, and was applied to the base of the trees receiving treatment on June 30 to a depth of 10 cm (4”) above the ground. This mulch type was selected because it is readily available in Toronto, is relatively inexpensive, and can be easily obtained and applied to private and public trees by homeowners and *Parks, Forestry and Recreation* workers from the City of Toronto. Despite the higher C:N ratio associated with wood chips, this type of mulch is commonly used in cityscapes due to the many benefits it is purported to deliver such as, soil temperature moderation, promotion of soil moisture retention, and weed suppression, in addition to supplying nutrients to the soil overtime.

Prior to applying mulch, the area of grass corresponding to the three treatment types was removed using a grass trimmer. The grass around the nutrient test reference plots (trees 13-15) was also removed in accordance with the area of the three treatment types in order to maintain homogeneity between the treated and untreated plots. This was important because, had the grass not been removed prior to mulch application, it would not have been possible to associate changes in soil nutrient availability to the application of mulch or to the decomposition of grass covered by mulch. Since the reference plots had no grass and no mulch, it was necessary for the treatment plots to have no grass and mulch so as to remove grass decomposition as a confounding variable. Grass growing proximate to the additional reference trees (1, 10 and 12; used for measurement of soil physical characteristics) was not removed so as to retain conditions that are typical in many urban park settings. The removal of grass is known to result in very high soil temperatures and low soil moisture (Watson, 1988; Iles and Dosmann, 1999); it was important to maintain this grass for the complementary research projects being conducted. All grass and weeds emerging from the soil in the reference plots throughout the duration of the experiment were removed with a grass trimmer or hand pulled. Within the treatment plots, any emerging grass or weeds were also removed.

3.3.4 Measurement of Soil Chemical and Physical Factors

In May, 2011(before mulching) baseline soil conditions throughout the site and for each study tree were assessed (Table 3.2). Precipitation, solar radiation, air temperature, and relative humidity sensors, recording data every 15 minutes, were mounted to a pole at the north side of the site until the end of October, 2011.

Table 3.2: Chemical and physical properties of soil measured and methods of measurement

PROPERTY	METHOD OF MEASUREMENT	FREQUENCY OF MEASUREMENT
Chemical		
pH	Soil core (SGS Agrifood Laboratories, Guelph)	Once (October 2011)
Salinity	Soil core (Ryerson lab)	Once (October 2011)
Soil organic matter	Soil core (SGS Agrifood Laboratories, Guelph)	Once (October 2011)
Nutrients (NO_3^-, NH_4^+, P, K, S, Ca, Mg, Fe, Cu, Zn, and Mn)	Anion-exchange and cation-exchange PRS^{TM}-Probes	Six x 28 days
Physical		
Precipitation	Rainfall collection bucket (pole mounted)	Every 15 min for 6 months
Solar radiation	Solar radiation sensor (W/m^2) (pole mounted)	Every 15 min for 6 months
Relative humidity	Relative humidity sensor (pole mounted)	Every 15 min for 6 months
Air temperature	Air temperature sensor (pole mounted)	Every 15 min for 6 months
Soil moisture	20 soil moisture sensors (% volumetric water content - VWC) buried permanently	Every 15 min for 6 months
Soil temperature	20 temperature loggers sensors buried permanently	Every 60 min for 6 months
Soil compaction	Hand-held digital penetrometer	Once (October 2011)
Soil bulk density	Soil core (Ryerson lab)	Once (October 2011)
Soil texture analysis	Soil core (Ryerson lab)	Once (October 2011)

Twenty permanent subsurface sensors to measure soil moisture and 20 permanent subsurface sensors to measure soil temperature were installed among treated and untreated plots. Five soil moisture logging stations were installed between groups of two or three trees (Figure 3.3), which each contained the data recorder for four soil moisture sensors. Each tree had one soil moisture and one soil temperature sensor positioned at 0.60 m from the base of the tree. Trees 2, 9 and 10 had an additional sensor placed at 1.35 m (0.15 m from the edge of the mulch application), trees 5, 7 and 12 had an additional sensor placed at 0.85 m, and trees 8 and 11 had an additional sensor placed again at 0.60 m. In order to conceal the wires connecting the soil moisture sensors from the moisture logging station, a trench was excavated and the wires were buried within the soil.

The soil temperature sensors were buried beside the soil moisture probes at each location. The moisture sensors collected data every 15 minutes and the temperature sensors collected data every hour due to the data storing capacity of the equipment.

Soil compaction was measured using a hand-held digital penetrometer once during the experimental period when soil moisture conditions were high (at the upper end of field capacity); soil compaction was expected to change little over the first growing season following application of organic mulch. Salinity, pH, bulk density, and organic matter content (also expected to change gradually) were assessed from soil cores taken at each of the treated and untreated plots once at the end of the experimental period in mid-October.

3.3.4.1 Nutrients

In order to measure the content of various nutrients in the soil, PRS™-probes were obtained from Western Ag Innovations in Saskatchewan. Twelve complete analysis PRS™-probes, which measured NO_3^-, NH_4^+, P, K, S, Ca, Mg, Fe, Cu, Zn, and Mn were inserted vertically into the soil profile (corresponding to the upper 15 cm of soil) every 28 days throughout May, June, July, August, September, and October of 2011 (for a total of 72 samples). During the first two time periods (May 2-30 and May 30-June 27) the baseline available nutrient conditions of the site were measured. The remaining four time periods (June 27-July 25, July 25-August 22, August 22-September 19, and September 19-October 17) measured conditions after the application of mulch. Four anion and four cation probes (15 cm x 3 cm x 0.5 cm in size) were paired and buried at each tree in the soil beneath treatment and reference plots at approximately 90 degree separation angles. The probes were inserted by making a slit in the soil with a spade and then pressing the slit closed to ensure the soil was in contact with the membrane portion of the probe. The four pairs of probes were then combined for a single analysis. Combining the probes for analysis accounted for soil heterogeneity within each replicate, much like a composite soil sample.

In order to test for the nutrient supply rate as the areal extent of mulch application was increased, the probes were placed a distance of 0.60 m from the base of the tree at each of the cardinal directions (north, south, east, and west). This distance was chosen because 0.60 m is the average size of a newly planted root ball. The probes were buried among plant roots, which gives an indication of the nutrient supply rate a tree root in the same soil area would experience.

A cumulative measure of nutrient supply throughout the growing season was measured by removing the buried PRS™-probes after 28 days and then re-inserting fresh probes in the same soil slot. After removal and washing with deionized water to remove all soil particles, the PRS™-probes were delivered to Western Ag Innovations for analysis. At the end of the growing season, the cumulative nutrient supply rates from the repeated burials were combined into two categories – “before mulching” and “after mulching”. These values were analyzed to assess the changes in nutrient supply *in situ* over time for each treatment type.

3.3.5 Statistical Analysis

In order to determine if there was a difference in each nutrient supply rate between mulch treatment types and time of mulch application (pre-mulch versus post-mulch), Analysis of Covariance (ANCOVA) was conducted using Systat (Version 13, Systat Corporation, Chicago, IL). This type of statistical test is commonly used when several other independent variables may contribute to the explanation of a certain phenomenon. In this study, nutrient supply rates among treatment plots may have been influenced by other soil chemical and physical factors despite spatial randomness of treatments. These other factors (covariates) included: soil compaction, bulk density, pH, organic matter, salinity, solar radiation, ambient air temperature, precipitation, and relative humidity. Data for each of these covariates were aggregated over six 28-day periods in accordance with the nutrient data collected from the PRS^{TM}-Probes.

Prior to conducting the ANCOVA test, Analysis of Variance (ANOVA) was used to determine if there was a difference among mulch treatments before mulch application, with the expectation that there should be no difference. Nutrients that exhibited a difference among treatments ($p<0.05$) were removed from the dataset and not analyzed using ANCOVA.

For each nutrient, a general linear model was initially run including all covariates. Any covariates that had little explanatory power ($p>0.05$) or were not linearly related to the dependent variable (tested using an ordinary least squares (OLS) regression analysis) were removed from the dataset and the analysis was run again in an attempt to increase the statistical strength of the outcome. ANCOVA model residuals were then tested to determine if their distribution approximated normal using the Kolmogorov-Smirnov-Lillifors test for normality. For nutrients that did not have normally distributed residuals ($p<0.05$), the raw data was $\log_{10}$ transformed and the ANCOVA model was run again, following the aforementioned steps to identify suitable covariates. The final model included only primary factors of interest (i.e., treatment type, time of mulch application, and the interaction between treatment type and mulch application) and statistically significant covariates. The model least squares (LS) adjusted mean values, and their associated 95% confidence intervals (CI), were documented for each nutrient. The model LS adjusted means are reflective of nutrient supply rates computed from the general linear model after adjusting for the covariate effect. The CIs were determined by multiplying 1.96 times the lower standard error (SE) and subtracting it from the LS adjusted mean, and multiplying 1.96 times the upper SE and adding it to the LS adjusted mean.

Due to instrument malfunction, permanent soil moisture and soil temperature data were not available for each of the six time periods, and therefore, could not be included in the ANCOVA as covariates. An additional analysis was conducted to determine if soil moisture was significantly different before and after mulch application with only five time periods included. This was complemented by an investigation of soil moisture retention among treatments during a three-week period of drought between July 1st and 21nd, 2011. Soil temperature was analyzed between June 15 and August 15, 2011 from data collected from eight sensors (two sensors each for 0.75m and 1.5m treatments and four sensors for reference plots with grass). The purpose was to determine the ability of mulch to buffer fluctuating soil temperatures.

3.4 Results

3.4.1 ANOVA Analysis

All nutrients except Zn, Fe, and Mn showed no difference ($p>0.05$) between treatment type (mulch ring radius) before mulch application (Table 3.3). These three nutrients were removed from the dataset and were not analyzed further.

Table 3.3: The effect of treatment before mulch application for each nutrient

Nutrient	P-value	F-ratio ($F_{3,16}$)
NO3	0.257	1.483
NH4	0.422	0.992
P	0.117	2.296
K	0.541	0.745
S	0.657	0.547
Ca	0.571	0.691
Mg	0.381	1.091
Fe	0.020	4.334
Mn	0.005	6.335
Cu	0.394	1.058
Zn	0.014	4.807

3.4.2 Analysis of Covariance

Kolmogorov-Smirnov-Lillifors test for normality on the residuals from each ANCOVA model determined that only models with the dependent variables S (p=0.196), Ca (p=0.200), and Mg (p=0.200) had residuals that approximated a normal distribution. Once $\log_{10}$ transformed, the distribution (evaluated using Kolmogorov-Smirnov-Lillifors test) of the residuals resulting from the remaining soil nutrient ANCOVA models also approximated normal: NO_3^- (p=0.054), NH_4^+ (p=0.200), K (p=0.200), P (p=0.200), and Cu (p =0.200). Due to severe outliers (likely resulting from animal activity) in the data, period 5 was removed from the NH_4^+ analysis and period 6 was removed from the NO_3^- analysis.

3.4.2.1 Nitrate

Mulching had an effect on soil NO_3^- supply rates (µg/10cm^2/28 days). There was a significant difference among treatments ($F_{3,48}$=5.299, p=0.003), and there was a significant mulching and treatment interaction ($F_{3,48}$=3.378, p=0.026) (Figure 3.4). However, there was no significant difference in NO_3^- supply rates before mulching versus after mulching ($F_{1,48}$=0.336, p=0.565); (pre-mulch = 9.59 µg/10cm^2/28 days, 95% CI [5.40, 14.84]; post-mulch = 7.73 µg/10cm^2/28 days, 95% CI [5.04, 10.91]). Overall, the 1.5 m treatments had the greatest NO_3^- supply rates (22.50 µg/10cm^2/28 days, 95% CI [8.01, 43.63]) compared to the other plots (0.75 m = 9.52 µg/10cm^2/28 days, 95% CI [4.05, 16.97]; 1.0m = 2.44 µg/10cm^2/28 days, 95% CI [0.75, 4.68]; reference = 9.09 µg/10cm^2/28 days, 95% CI [1.59, 21.17]). Soil NO_3^- supply rates covaried with bulk density (p<0.001), organic matter (p=0.001), salinity (p=0.022), and air temperature (p=0.026).

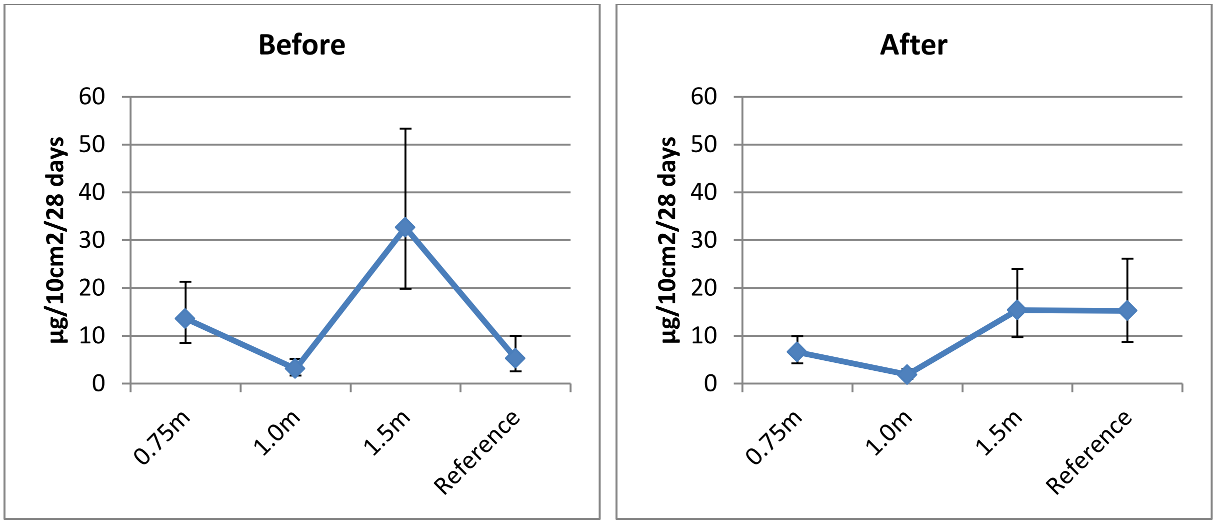


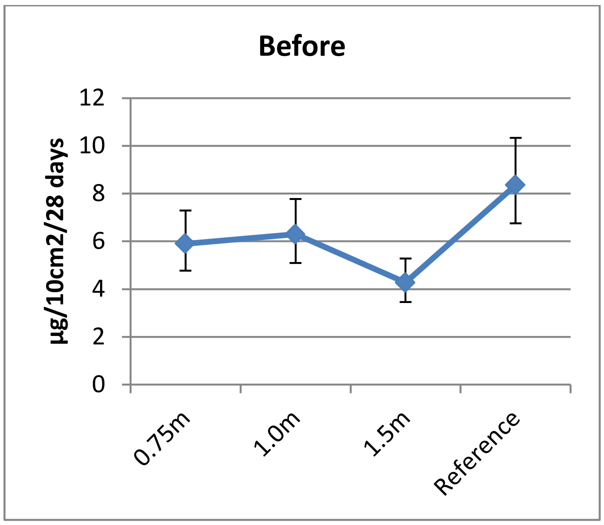
Figure 3.4: Least squares adjusted means for NO_3^- supply rate (µg/10cm^2/28 days) for each treatment type before and after mulch application including standard error

3.4.2.2 Ammonium

Mulching did not have an effect on soil NH_4^+ supply rates (µg/10cm^2/28 days). There was no significant difference among plots before mulching versus after mulching ($F_{1,51}$=1.164, p=0.286); (pre-mulch=1.01 µg/10cm^2/28 days, 95% CI [0.40, 1.75]; post-mulch=2.55 µg/10cm^2/28 days, 95% CI [0.91, 2.29]). There was also no difference among treatments ($F_{3,51}$=0.382, p=0.767); (0.75 m = 1.49 µg/10cm^2/28 days, 95% CI [0.53, 2.68]; 1.0 m = 1.31 µg/10cm^2/28 days, 95% CI [0.42, 2.41]; 1.5 m = 1.11 µg/10cm^2/28 days, 95% CI [0.30, 2.13]; reference = 1.19 µg/10cm^2/28 days, 95% CI [0.35, 2.24]). There was no significant interaction between mulching and treatment type ($F_{3,51}$=1.221, p=0.312). Soil NH_4^- supply rates covaried with precipitation (p=0.002).

3.4.2.3 Phosphorus

Mulching had an effect on soil P supply rates (µg/10cm^2/28 days). There was a significant treatment and mulching interaction ($F_{3,62}$=3.166, p=0.031) (Figure 3.5). However, there was no difference among plots before mulching versus after mulching ($F_{1,62}$=1.916, p=0.171); (pre-mulch = 6.04 µg/10cm^2/28 days, 95% CI [4.70, 7.55]; post-mulch = 7.50 µg/10cm^2/28 days, 95% CI [6.39, 8.70]). There was also no difference among treatments ($F_{3,62}$=0.846, p=0.474); (0.75 m = 7.33 µg/10cm^2/28 days, 95% CI [5.65, 9.23]; 1.0 m = 7.21 µg/10cm^2/28 days, 95% CI [5.56, 9.08]; 1.5 m = 5.71 µg/10cm^2/28 days, 95% CI [4.41, 7.20]; reference = 6.79 µg/10cm^2/28 days, 95% CI [5.24, 8.55]). Soil P supply rates covaried with precipitation (p<0.001) and air temperature (p<0.001).



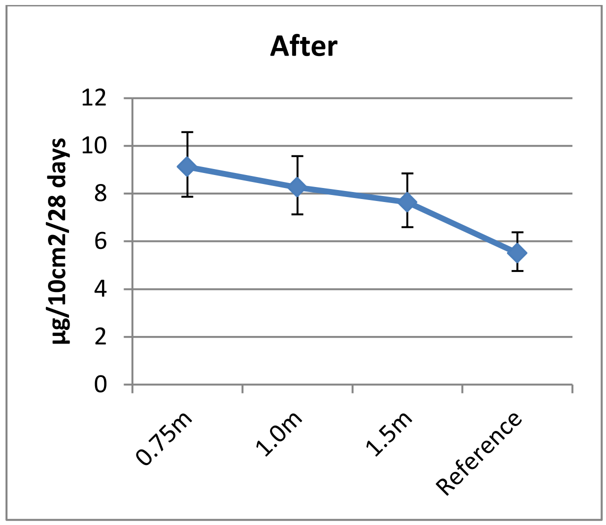


Figure 3.5: Least squares adjusted means for P supply rate (µg/10cm^2/28 days) for each treatment type before and after mulch application including standard error

3.4.2.4 Potassium

Mulching had no effect on soil K supply rates (µg/10cm^2/28 days). There was no significant difference among plots before mulching versus after mulching ($F_{1,62}$=1.595, p=0.211); (pre-mulch = 66.53 µg/10cm^2/28 days, 95% CI [50.49, 84.81]; post-mulch = 82.60 µg/10cm^2/28 days, 95% CI [69.04, 97.41]). There was also no difference among treatments ($F_{3,62}$=1.185, p=0.323); (0.75 m = 68.23 µg/10cm^2/28 days, 95% CI [46.76, 93.81]; 1.0 m = 66.07 µg/10cm^2/28 days, 95% CI [48.84, 85.94]; 1.5 m = 59.02 µg/10cm^2/28 days, 95% CI [37.80, 85.00]; reference =

113.50 µg/10cm^2/28 days, 95% CI [59.79, 184.30]). There was no significant interaction between mulching and treatment type ($F_{3,62}$=2.265, p=0.090). Soil K supply rates covaried with salinity (p=0.017) and air temperature (p<0.001).

3.4.2.5 Sulfur

Mulching had an effect on soil S supply rates (µg/10cm^2/28 days). There was a significant difference among plots before mulching versus after mulching ($F_{1,62}$=8.438, p=0.005); however, there was no difference among treatments ($F_{3,62}$=2.057, p=0.115); (0.75 m = 57.41 µg/10cm^2/28 days, 95% CI [25.58, 89.24]; 1.0 m = 60.10 µg/10cm^2/28 days, 95% CI [30.54, 89.66]; 1.5 m = 91.99 µg/10cm^2/28 days, 95% CI [62.51, 121.47]; reference = 109.43 µg/10cm^2/28 days, 95% CI [77.34, 141.52]). There was also no significant treatment and mulching interaction ($F_{3,62}$=2.255, p=0.091). Overall, average S supply rates decreased following mulch application (pre-mulch = 101.49 µg/10cm^2/28 days, 95% CI [77.68, 125.42]; post-mulch = 57.98 µg/10cm^2/28 days, 95% CI [41.10, 74.86]). Soil S supply rates covaried with precipitation (p<0.001) and bulk density (p<0.001).

3.4.2.6 Calcium

Mulching had an effect on soil Ca supply rates (µg/10cm^2/28 days). There was a significant difference among plots before mulching versus after mulching ($F_{1,63}$=38.889, p<0.001); however, there was no significant difference among treatments ($F_{3,63}$=1.363, p=0.262); (0.75 m=2327.75 µg/10cm^2/28 days, 95% CI [2128.73, 2526.77]; 1.0 m=2108.23 µg/10cm^2/28 days, 95% CI [1909.21, 2307.25]; 1.5 m = 2278.50 µg/10cm^2/28 days, 95% CI [2079.48, 2477.52]; reference = 2382.38 µg/10cm^2/28 days, 95% CI [2183.36, 2581.40]). There was also no significant interaction between mulching and treatment type ($F_{3,63}$=0.383, p=0.766). Overall, average Ca supply rates decreased following mulch application (pre-mulch = 2592.63 µg/10cm^2/28 days, 95% CI [2429.52, 2755.74]; post-mulch = 1955.80 µg/10cm^2/28 days, 95% CI [1840.69, 2070.91]). Soil Ca supply rates covaried with precipitation (p<0.001).

3.4.2.7 Magnesium

Mulching had an effect on soil Mg supply rates (µg/10cm^2/28 days). There was a significant difference among plots before mulching versus after mulching ($F_{1,61}$=32.283, p<0.001), and among treatments ($F_{3,61}$=3.815, p=0.014). However, there was no significant mulching and treatment interaction ($F_{3,61}$=0.628, p=0.599). Overall, average Mg supply rates decreased following mulch application (pre-mulch = 181.67 µg/10cm^2/28 days, 95% CI [169.95, 193.39]; post-mulch = 137.17 µg/10cm^2/28 days, 95% CI [129.51, 144.83]). The 0.75 m plots had the greatest Mg supply rate (174.53 µg/10cm^2/28 days, 95% CI [160.99, 188.07]), followed by the 1.5 m plots (163.07 µg/10cm^2/28 days, 95% CI [149.29, 176.85]), and the 1.0m plots (155.52 µg/10cm^2/28 days, 95% CI [142.64, 168.40]). The reference plots had the lowest Mg supply rates (144.55 µg/10cm^2/28 days, 95% CI [131.83, 157.27]). Soil Mg supply rates covaried with precipitation (p<0.001), air temperature (p=0.010), and soil pH (p=0.001).

3.4.2.8 Copper

Mulching had an effect on soil Cu supply rates (µg/10cm^2/28 days). There was a difference among plots before mulching versus after mulching ($F_{1,63}$=59.803, p<0.001); however, there was no difference among treatments ($F_{3,63}$=1.180, p=0.324); (0.75 m = 1.98 µg/10cm^2/28 days, 95% CI [1.43, 2.63]; 1.0 m = 1.35 µg/10cm^2/28 days, 95% CI [0.97, 1.79]; 1.5 m = 1.74 µg/10cm^2/28 days, 95% CI [1.25, 2.31]; reference = 1.85 µg/10cm^2/28 days, 95% CI [1.33, 2.45]). There was also no significant mulching and treatment interaction ($F_{3,63}$=0.138, p=0.937). Overall, average

Cu supply rates decreased following mulch application (pre-mulch = 3.13 µg/10cm^2/28 days, 95% CI [2.40, 3.95]; post-mulch = 0.94 µg/10cm^2/28 days, 95% CI [0.78, 1.11]). Soil Cu supply rates covaried with precipitation ($p<0.001$).

3.4.3 Soil Moisture

There was a significant difference between average soil moisture (%) before and after mulch application for each treatment type. For 0.75 m treatment plots, soil moisture before mulching ($\bar{x}$=28.6%, SD=3.9%) was higher than soil moisture after mulching ($\bar{x}$=21.8%, SD=3.0%); $t_{(8.9)}$= 3.637, p=0.006. Similarly, 1.0 m treatment plots had a greater soil moisture before mulching ($\bar{x}$ =29.7%, SD=3.3%) versus after mulching ($\bar{x}$=23.0%, SD=3.1%); $t_{(12)}$= 3.942, p=0.002. The 1.5 m treatment plots also showed a higher soil moisture before mulching ($\bar{x}$=27.4%, SD=2.1%) compared to after mulching ($\bar{x}$=23.3%, SD=3.9%); $t_{(12.6)}$= 2.647, p=0.021 (Appendix A).

During the drought period of July 1 to July 21, 2011, a statistically significant difference between treatment types ($F_{3,15}$=8.761, p=0.001) was observed using soil organic matter (%) as a covariate (p=0.027). Average soil moisture (%) loss was greatest in the reference plots with grass (reference=-9.80%, SE=0.72%) compared to the treatment plots (0.75 m=-6.56%, SE=0.56%; 1.0 m =-4.84%, SE=1.02%; 1.5 m=-5.45%, SE=0.75%) (Figure 3.6).

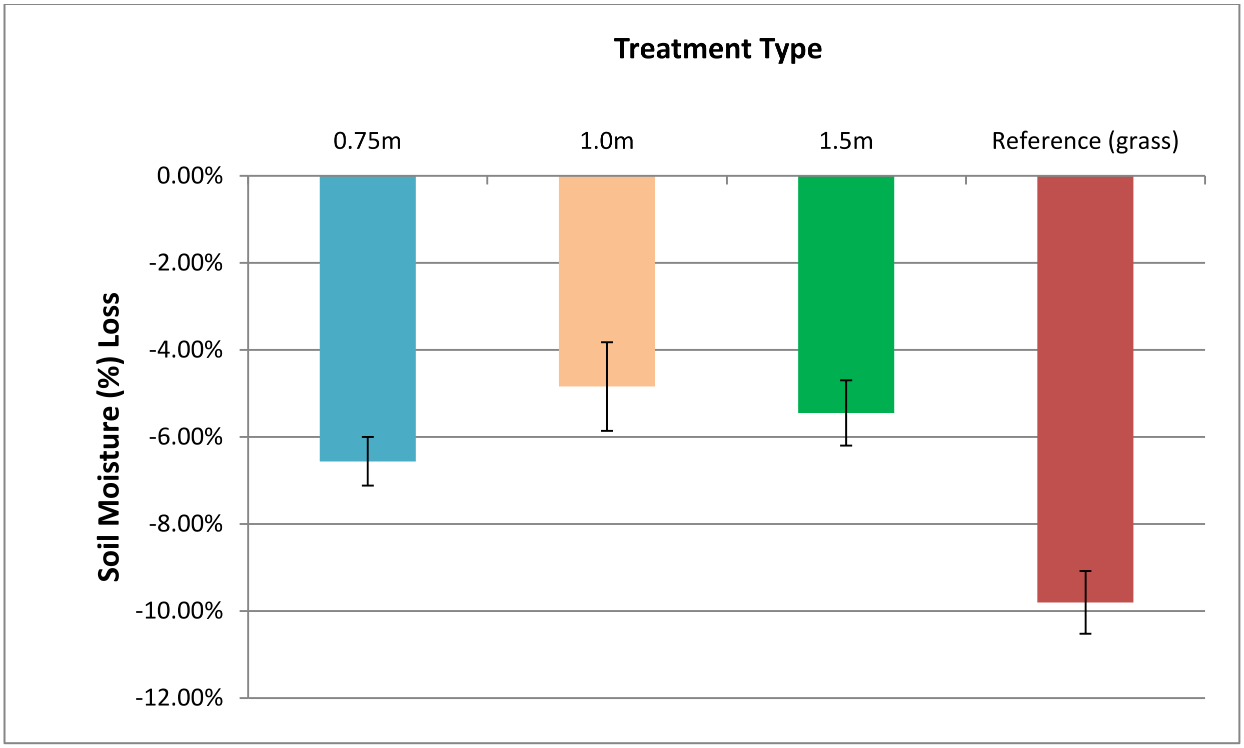


Figure 3.6: Average soil moisture (%) loss over a 21 day drought from July 1-21, 2011 for each treatment type with standard error

3.4.4 Soil Temperature

The application of mulch had a significant impact on buffering soil temperatures during the period of June 15 to August 15, 2011. The untreated soil rooting zone (reference trees with grass) experienced large fluctuations in soil temperature compared to the soil rooting zones treated with mulch. Also, mulch appeared to provide an important buffer against very hot ambient temperatures in mid/late July. Overall, the 1.5 m mulch rings had a larger impact on temperature moderation than the 0.75 m mulch rings (Figure 3.7).

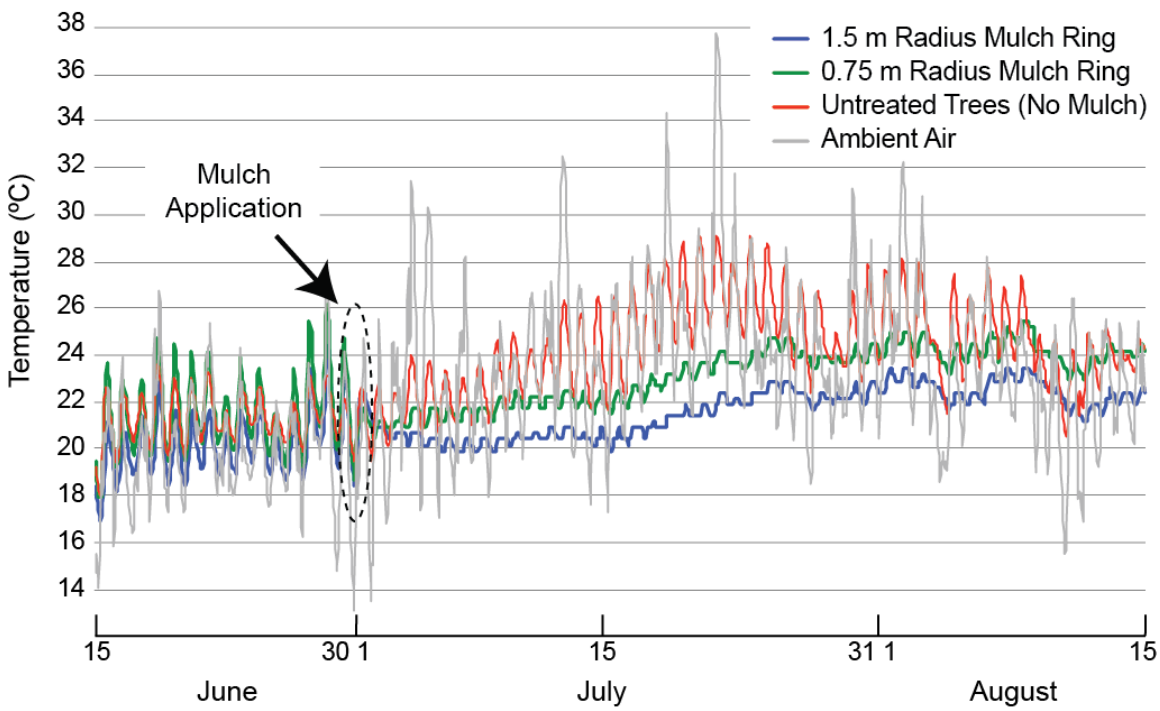


Figure 3.7: Temperature (°C) comparison between mulched and non-mulched trees during the period of June 15 to August 15, 2011

3.4.5 Soil Compaction

Average soil compaction (0-20 cm in depth) between trees ranged from 975 kPa to 2549 kPa with an overall average soil compaction of 1673 kPa. There was a significant difference between soil compaction and treatment type ($F_{4,10}$=6.612, p=0.007). Overall, the 0.75 m treatments had a higher soil compaction value (2444 kPa, SE=181.12) compared to the 1.0 m treatments (1451 kPa, SE =181.12), the 1.5m treatments (1326 kPa, SE=181.12), reference plots with no grass (1365 kPa, SE=181.12), and reference plots with grass (1776 kPa, SE=181.12) (Appendix C).

3.4.6 Other Soil Chemical and Physical Factors

The soil pH between trees ranged from 7.18 to 7.73 with an average pH of 7.49. There was no significant difference in soil pH among treatment types ($F_{3,8}$=2.188, p=0.167). The organic matter content between trees ranged from 2.3% to 5.6% with an average of 3.8%. Similar to soil pH, there was no significant difference in organic matter content among treatment types ($F_{3,8}$=3.018, p=0.094). The bulk density between trees ranged from 1.20 Mg/m^3 to 1.82 Mg/m^3 with an average of 1.46 Mg/m^3; no significant difference in bulk density among treatment types was found ($F_{3,8}$=1.320, p=0.334). Soil salinity (measured as electrical conductivity) ranged from 0.06 EC_{SE} to 2.40 EC_{SE}, with an average salinity of 1.25 EC_{SE}. A significant difference in soil salinity among treatment types ($F_{3,8}$=13.566, p=0.002) was found. Overall, the reference plots had the greatest salinity value (2.03 EC_{SE}, SE = 0.155) compared to the 0.75 m treatment (0.90 EC_{SE}, SE = 0.16), the 1.0 m treatment (1.30 EC_{SE}, SE = 0.16), and the 1.5 m treatment plots (0.77 EC_{SE}, SE = 0.16) (Appendix D). There was a negative correlation between percent organic matter and bulk density (r =-0.922, p<0.001), and percent organic matter and soil pH (r=-0.848, p<0.001).

3.4.7 Meteorological Data

Average air temperature (°C) was greater after mulch application ($\bar{x}$=20.47, SD=4.80) compared to before mulch application ($\bar{x}$=15.94, SD=4.45); $t_{(14869)}$=31.254, p<0.001. Average solar radiation (W/m^2) was greater before mulch application ($\bar{x}$=203.19, SD=274.17) compared to after mulch application ($\bar{x}$=186.53, SD=262.32); $t_{(10129)}$ = 8.873, p<0.001. Average relative humidity (%) was greater before mulch application ($\bar{x}$=74.44, SD=18.17) compared to after mulch application ($\bar{x}$=73.49, SD=14.80); $t_{(9315)}$ = 2.992, p=0.003. There was no difference in average total precipitation before mulch application compared to after mulch application; $t_{(17846)}$=0.242, p=0.809 (Appendix E).

3.5 Discussion

3.5.1 Nutrient Supply Rates

Application of mulch had an impact on the supply rates of some nutrients investigated. No nutrients showed an increase in supply rate after mulch application across all treatments and the reference plots; however, the supply rates of S, Ca, Mg, and Cu decreased in all plot types following the application of mulch. Only NO_3^- and Mg showed a difference in supply rates among treatments throughout the entire growing season. For Mg, the 0.75 m radius of mulch had the greatest supply rates, while the reference plots had the lowest. In the case of NO_3^-, the 1.5 m radius had the greatest supply rates due to a high value before mulch application, while the 1.0 m radius had the lowest. NO_3^- and P were the only two nutrients that showed a significant mulching and treatment interaction, which means that the difference in supply rate before and after mulch application was dependent on treatment. For P supply rates, the 0.75 m and 1.5 m treatments both increased post-mulching, while the reference plots decreased post-mulching. The 1.0 m plots also appeared to increase post-mulching. This suggests that mulch plays an important role in making P more bioavailable for plant roots. For NO_3^-, the only difference was a decrease in supply rates in the 1.5 m treatments following mulch application. The high value before mulch application may be due to site specific conditions or the result of a large volume of wood chips providing a high C:N ratio, which may have led to microbial competition for N.

Over the growing season, it was expected that the supply rates would change since the demand for nutrients by trees also changes over time. Sinclair *et al*. (1990) observed a greater concentration of Cu in the soil during the earlier months of the summer compared to later in the season, which is similar to the Cu, Ca, Mg, and S supply rates observed in this study. This is likely attributed to plant demand for these nutrients early in the season for photosynthesis and plant growth (Marschner and Rengel, 2012). During the later months of the growing season, soil nutrient availability decreases as roots exhaust the nutrient pool, especially if nutrients are not replenished through microbial activity, mineralization, weathering, or fertilizers (Craul, 1992). Since there was no difference in Cu, Ca and S supply rates between treatments and the reference plots, it is likely that changes in these nutrient supply rates in the soil were not influenced by mulch application (or mulch decomposition), but rather by temporal variations in plant demand and environmental factors, such as precipitation and temperature. The supply rates for these nutrients also remained within or higher than the range of values typically found in non-sandy mineral soils throughout the growing season, indicating that they were in sufficient supply. For instance, all supply rates for S were within the range (or higher in some cases) of 2 to 300 µg/10cm^2/4 weeks reported in natural forested soils (Western Ag Innovations, 2010). Ca levels were also within the supply rate range of 1000 to 3000 µg/10cm^2/burial time reported in non-sandy mineral soils. Cu levels were generally greater than the typical values of 0.1 to 0.5 µg/10cm^2/burial time; however, this may be attributed to higher levels of precipitation and soil moisture during certain time periods (Bremer, personal communication). The same reasoning can be used to explain Mg supply rates. The lower Mg supply rate for the reference plots is likely due to random natural variation in available Mg found in the soil of these trees. However, the same declining trend was observed as seen for Cu, Ca, and S, and the Mg supply rates were within the reported range of 40 to 400 µg/10cm^2/burial time (Gastaldello *et al*., 2007; Bremer, personal communication).

For P, the increase in supply rates after mulch application may be explained by several factors, including the decomposition of the wood chips and the promotion of fungal colonization, which can both be associated with delivery of P to the soil. All three treatment types showed an increase in P supply rates after mulch application, while the reference plots showed a decrease, which may be indicative of the lack of decomposing wood chips. Most of the N and P found in soils are produced from the decomposition of organic matter and the recycling of these nutrients by microbial activity (Craul, 1992). Additionally, the wood chips may have created a favourable environment for fungal growth. In many soils, there is a pre-existing organic pool of P that must be hydrolyzed and converted into inorganic P before it becomes available for uptake by plant roots. This process occurs through the release of the enzyme, phosphatase, by fungi in the soil (Hull 1997b). In this study, the wood chips likely stimulated fungal growth by acting as a carbon source, and in turn, the fungi were able to liberate the P in the soil, increasing the P supply rates under mulched plots. Overall, the P supply rates in this study were moderate to very high compared to the range of 0.5 to 20 $\mu g/10cm^2/4$ weeks reported in disturbed and undisturbed forested soils (Gastaldello *et al*., 2007; Western Ag Innovations, 2010).

In addition, over the course of the growing season and into the next season (2012), the development of fine roots near the surface of the soil under the mulch was apparent. Watson (1988) also reported an increase in root surface area by 195 percent in mulched plots. While not measured (quantified) in this study, the presence of fine roots under the mulch is an important observation because these roots have a larger surface area and are responsible for the majority of nutrient and water absorption (Watson and Kelsey, 2006). A greater density of fine roots reduces the distance nutrients must travel both vertically and horizontally in the soil to reach the root interface (Marschner and Rengel, 2012). Othieno (1973) found that mulch significantly increased the concentration of roots found near the surface of the soil and helped to increase the utilization of P applied during fertilization. Studies have shown that the volume of root hair positively corresponds to the amount of P and K taken up by plant roots (Jungk, 2001; Marschner and

Rengel, 2012). In some instances, 50-97% of the total P uptake can be attributed to root hairs (Othieno, 1973; Föhse *et al*., 1991). In the present study, only P showed an increase among the three treatments after the application of mulch; however, as the mulch continues to decompose, it is possible the same trend will be observed for K supply rates. Compared to the range of 8 to 900 $\mu g/10cm^2$/burial period reported in disturbed and undisturbed forested soils (Johnson *et al*., 2008; Western Ag Innovations, 2010), K supply rates were moderate in this study.

For NH_4^+, there was no significant difference in supply rates before and after mulch application. For NO_3^-, there was a small decrease in supply rates for the 1.5 m treatment after mulch application and a small increase in supply rates for the reference plots; the 0.75 m and 1.0 m plots did not show a difference pre-mulching versus post-mulching. This finding indicates that there might be some competition by microbes for NO_3^- due to a high wood chip C:N ratio; however, this did not seem to be an issue for NH_4^+ supply rates. Billeaud and Zajicek (1989) reported similar results when testing the effect of four different mulching materials on soil N concentration, along with other factors such as weed control and pH levels. In their study, under all treatment conditions, N concentrations were lower in soils where mulch was applied. However, the authors found that when a weed barrier fabric was placed between the soil and each of the four mulch types, N concentrations in the soil remained higher than mulch plots without a weed barrier since microbes were unable to access the N. In the present study, time period six was removed from the NO_3^- dataset due to very high nutrient supply rates reported for the reference plots, which skewed the data positively. Since the reference plots did not have any ground cover (just exposed soil), there was likely a very small microbial population, reducing N competition and allowing more NO_3^- to be made available for plant uptake over the course of the growing season. In the treatment plots, there was likely some microbial competition, which may explain why NO_3^- supply rates did not change (and decreased slightly in some instances) compared with reference plots. In saline soils, Cl^- often competes with NO_3^-, reducing uptake by plant roots (White, 2012); however, this does not adequately explain the findings of this study. The reference plots demonstrated the greatest average salinity (EC_{SE}) and also the largest supply rate of NO_3^-, indicating that salinity was not a limiting factor.

The reduction in N due to microbial competition will hopefully be minimized over the course of several growing seasons as the mulch continues to decompose and microbes die, which will release N back into the soil. The total N supply rate (NO_3^- and NH_4^+) was fairly low among treated plots, with a significantly lower amount of NH_4^+ compared to NO_3^-. In disturbed and undisturbed forested soils tested using PRS™-Probes, NO_3^- supply rates ranged from <1 to 260 µg/10cm²/burial period, while NH_4^+ supply rates ranged from <1 to 400 µg/10cm²/burial period (Koehn et al., 2002; Gastaldello *et al*., 2007; Hope, 2007; Johnson *et al*., 2008; Western Ag Innovations, 2010; Brockett *et al*., 2012). In the present study, NO_3^- supply rates were low to moderate when compared with the above values; whereas, NH_4^+ supply rates were very low to low. Several plots were even below method detection limits for NH_4^+ in some time periods (mainly time periods two and six, but also for some trees in time periods one and four), which is concerning because N is an essential nutrient required for several plant physiological and metabolic functions. Having adequate bioavailable NH_4^+ in the soil is very important since tree roots typically favour NH_4^+ over NO_3^- as the primary source of N. Marschner *et al.* (1991) found that Norway spruce trees favoured NH_4^+ and only utilized the NO_3^- in the soil when the concentration of NH_4^+ was less than 100µM. Two options for increasing N availability in soils where N appears to be depleted are to apply wood chip mulch blended with compost or to administer a fertilizer.

Precipitation and air temperature (closely related to soil moisture and soil temperature) showed the greatest co-variation with nutrient supply rates when compared with all other covariates investigated. These covariates are likely to play a larger role in influencing mulch decomposition and releasing nutrients into the soil (e.g., warmer and wetter soil causes more rapid decomposition and may lead to more nutrient availability) (Johnson *et al*., 2008). Other factors such as compaction (which did not show any co-variance) and bulk density (which only covaried with two nutrients), typically take longer to alter (often many years), and do not influence nutrient availability as great as soil moisture and soil temperature, which can be influenced by mulch over a much shorter time span (days to months) (Hawver and Bassuk, 2007). For example, Ca, Mg, and S nutrient supply rates, which all covaried with precipitation, were noticeably lower in periods of low rainfall (time periods three and five). The low supply rates of these nutrients may also explain the higher K supply rates during these time periods, as Ca and Mg often displace K ions in the soil when present in large quantities (White, 2012). Cu supply rates also covaried with precipitation and were found to be greater during higher rainfall periods; however, organic matter and pH, which have a large influence on Cu availability in the soil, did not show a significant covariance with Cu availability. Cu is typically lower in alkaline soils and in soils with higher amounts of organic matter because it forms weakly soluble salts with carbonate and hydroxide and binds to organic substances (Hull, 2002b; Broadley *et al*., 2012). NO_3^- covaried with bulk density and organic matter, which may be explained by the fact that decomposition of organic matter provides most of the N released into the soil.

3.5.2 Soil Moisture

The three treatment types all showed greater soil moisture content before mulch application compared with after. This was expected since snowmelt increases the saturated flow of water in the soil at the beginning of the growing season. As the season progresses, the soil becomes less saturated as tree roots absorb water and evaporation occurs due to warming temperatures. In addition, the water begins to leave the top soil horizons and percolate through the soil column to deeper levels (i.e., contributing to groundwater) (Craul, 1992). The amount of precipitation over the growing season will also impact soil moisture content. During this study, time periods three and five had significantly less total precipitation; however, overall, there was no difference in total average precipitation during the four months after mulch application compared to the two months before mulching.

Despite the reduction in soil moisture content post-mulching, the wood chips acted as a protective barrier to high air temperatures and evaporation during the drought period of July 1 to July 21. All treatment plots showed a significantly lower loss of soil moisture compared to the reference plots. This supports the literature that mulch plays an important role in increasing soil moisture retention and restricting soil moisture loss through evaporation. Iles and Dosmann (1999) reported the lowest soil moisture percentages in non-mulched control plots compared to eight different mulch treatments. Similarly, Litzow and Pellett (1983) found that the moisture content was greatest in the soil below the wood chips and redwood bark following a precipitation event compared to non-mulched treatments. Additionally, Watson (1988) reported the greatest moisture content in mulched plots, followed by bare soil, and then grassed plots. Although, soil moisture data for reference plots without grass were not available in this study, it would be interesting to see if the same trend might be found.

3.5.3 Soil Temperature

The ability of mulch to moderate fluctuating soil temperatures in the treatment plots compared to the reference plots was an important finding that supports the conclusions made by several other studies (Lal, 1974; Iles and Dosmann, 1999; Herms, 2001; Kumar and Dey, 2011; Li, 2011). In this study, the temperature probes were inserted at a depth of 10 cm below the surface, which is the depth where fine roots that are important for absorbing water and nutrients are located. Prior to mulch application, all plots experienced similar fluctuations in soil temperature. However, after the wood chip mulch was applied, the treated rooting zones maintained lower and steadier temperatures compared to the non-treated rooting zones that experienced large fluctuations and much warmer temperatures. There is little data available in the literature regarding the effect of high soil temperatures on the growth of common urban trees (Graves, 1994). However, Graves *et al*. (1989) reported that a root zone temperature of 24°C is optimal for leaf area, stem length, and root-to-shoot ratios in the common urban tree, Tree of Heaven (*Ailanthus altissima* L.). On the other hand, urban trees, honeylocust (*Gleditsia triacanthos*) and red maple (*Acer rubrum*), are able to tolerate higher temperatures up to 34°C. In general, most temperate tree species cannot tolerate soil temperatures greater than 25°C to 30°C. Prolonged temperatures above 30°C can be detrimental to root and shoot growth of most tree species (Graves, 1994). In the present study, the 1.5 m radius treatment plots were the only rooting zones that maintained soil temperatures less than 25°C, supporting the argument that a larger area of mulch provides more benefits to the rooting zone of trees. Additionally, soil moisture content has a large impact on the heat capacity of a soil, meaning that wet soils take longer to heat up than dry soils (Craul, 1992). Thus, soil moisture and soil temperature are interrelated, and the impact of mulching can provide direct and indirect benefits for both of these important rooting zone factors.

3.5.4 Soil Compaction

The trees at the south end of the site had lower average compaction values within the top 20 cm of the soil (less than 1500 kPa), likely attributed to their location away from the previously paved area to the north of the site and the vehicular compaction during the CNE. Trees at the north end had much higher average compaction values within the top 20 cm of the soil (as great as 2500 kPa), likely attributed to heavy and prolonged vehicular and pedestrian traffic. When the soil strength exceeds 2000 to 2500 kPa, root growth begins to stop and at compaction values as low as 700 kPa, the penetration of roots into the soil can be reduced by as much as half (Roberts *et al*., 2006). The majority of fine roots (less than 32 mm (1/8") in diameter) are found in the top 15 cm of the soil (Craul, 1992). This depth is most critical for nutrient and water absorption and root growth. Thus, reducing the level of compaction in the upper 15 to 20 cm of soil is essential for providing suitable growing conditions (sufficient soil pore space for adequate oxygen diffusion and water flow) for roots and maintaining stable and healthy trees.

Despite the reference plots having low compaction values within the top 20 cm of the soil, they experienced the greatest compaction values (between 4000 and 5000 kPa) at depths greater than 20 cm. Tree 2 also exhibited similar patterns; however, trees 1 and 3, which are located in the same vicinity, did not experience the same level of compaction at these depths. Variation in soil and parent material surrounding these trees that create horizons of compacted soil is a likely explanation for the differences noted. Unfortunately, the application of mulch will not influence soil compaction at great depths; however, overtime, a reduction in soil strength should be observed in the top layers of the soil.

3.5.5 Other Soil Chemical and Physical Factors

The bulk densities for the trees on the site were within and higher than the recommended values for healthy root growth. Aubertin and Kardos (1965) stated that root restriction typically occurs between bulk densities of 1.4 and 1.6 Mg/m^3 depending on the soil texture and tree species. Craul (1992) suggested that favourable tree growth in the subsoil can occur within bulk densities of 1.2 to 1.5 Mg/m^3. Similar to soil compaction, trees located on the southern portion of the site (trees 2, 3, and 13-15) experienced lower bulk density values (an average of less than 1.35 Mg/m^3); whereas, trees located to the north (trees 7-9), experienced the largest bulk densities (greater than 1.60 Mg/m^3).

Additionally, there appeared to be a correlation between percent organic matter and bulk density based on a high r-value. The amount of organic matter for all trees was within the range of 1 to 5 percent by weight that is recommended for non-limiting soils for tree planting (Craul, 1999). Trees 2, 3 and 13-15 all had the greatest percent organic matter content (greater than 4.5%); whereas, trees 7-9 had the lowest percent organic matter content (less than 3.0%). Although the amount of organic matter was within the recommended range, the values reported in this study are very low compared to forested soils. In order to improve nutrient uptake and tree growth, it is necessary for managers of urban parks to focus on increasing organic matter content around trees.

As organic matter decomposes, the structure and pore size distribution of the soil is positively affected. Rivenshield and Bassuk (2007) reported a reduction in bulk density to below root-restricting levels and greater macroporosity in both sandy and clay soils that were amended with sphagnum peat mulch and food waste compost. These authors also noted that the clay-loam soil required a greater percentage of organic matter compared to the sandy-loam soil to reduce bulk-density values to below root-restricting levels. Therefore, depending on the amount of organic matter, physical changes (i.e., alterations to bulk density) in clay soils may occur more slowly. Since the soil in this is study sandy clay loam, similar results will hopefully be reported overtime as the mulch continues to decompose and increases the pore space within the soil. Additionally, the mulch will hopefully deter pedestrians and motorists from walking and driving near the base of the trees and over the rooting zones. Restricting these forms of park use will help to alleviate further increases in bulk density and allow for mulch decomposition and organic matter development.

The pH of the soil was slightly alkaline and above the range of 6.0 to 7.0 for optimal nutrient solubility and tree growing conditions (Craul, 1992; Roberts *et al*., 2006; USDA, 2012a,b,c,d). Similarly, elevated pH levels as high as 9.0, have been reported in urban locations across Syracuse and Philadelphia (Bockheim, 1974; Craul and Klein, 1980; Ware, 1990). High pH values in urban areas may be attributed to street and sidewalk de-icing salts (sodium chloride or calcium carbonate), construction waste (often containing cement), and the weathering of concrete and other impervious surfaces (Craul, 1992; Mauro, 1997). A slightly lower pH value around trees in this study site would be more suitable for optimal nutrient acquisition and tree growth.

Trees 2 and 3,which both had high soil organic matter content after the first growing season, had the lowest pH values, supporting the argument that decomposition of organic matter provides an acidifying effect on the surrounding soil due to the release of organic acids (Craul, 1992). The reference plots had a slightly higher pH (although still lower than the trees with little organic matter), possibly because the organic matter had already been incorporated into the soil overtime and there was no fresh material being decomposed (especially since the grass had been removed). The higher pH values for the remaining plots may be explained by an abundance of urban fill (i.e., a soil matrix containing gravel and pieces of crushed concrete) found in the northern portion of the site.

Billeaud and Zajicek (1989) found that soil pH was lower in four different types of mulch compared to the control after six months of mulching. On the other hand, Iles and Dosmann (1999) reported higher soil pH values under shredded bark and wood chip mulches compared to non-mulched plots after two years. In the present study, only one pH measurement was taken during the first growing season, so changes in soil pH could not be observed. However, based on the results from Billeaud and Zajicek (1989) and Iles and Dosmann (1999), it is hypothesized that the mulched plots will see an initial reduction in pH due to the decomposition of the wood chips and the release of organic acids. As time progresses and an equilibrium is established (mulch is incorporated into the topsoil forming a humic layer), a stabilization in soil pH is expected that might be slightly higher than the initial value found shortly after application of mulch.

The salinity, measured in electrical conductivity (EC_{SE}), was low for all plots. EC_{SE} is measured in decisiemens per metre (ds/m), which is equal to one milimho per centimetre (mmho/cm). Salt concentrations between 0-2 mmho/cm are categorized as low, normal, and non-saline, and concentrations between 2-4 are categorized as very slightly saline, possibly restricting sensitive plants (Craul, 1992). All trees in this study had an EC_{SE} of less than 2 ds/m, except for two of the reference plots that were slightly above 2 ds/m. Overall, mulching seemed to provide a buffer against soil salinity levels in the treatment plots. However, given that the EC_{SE} values did not fall within the moderately saline, strongly saline, or very strongly saline categories, it can be noted that the salinity values for all plots within the study site are not at a level that would adversely affect plant root health.

3.6 Conclusion

The use of organic mulch to improve soil conditions is not a novel concept. The application of soil amendments to enhance the soil chemical and physical conditions necessary for plant health has been documented throughout the literature. While the study design limited this research from being able to determine whether a larger surface coverage of mulch had a greater potential to improve soil nutrient supply rates (i.e., limited number of soil nutrient probes), it is plausible to assume that, where treatment rings of a different size showed no difference in values, supply rate was constant in all soil covered by the mulch. Therefore, while larger rings may not have higher nutrient supply rates, they may have created conditions where supply rates have been altered for a much larger volume of soil.

Furthermore, given that this study only measured nutrient supply rates over one growing season, differences among treatment types may be observed overtime as the wood chips continue to decompose and release fresh nutrients into the soil. A greater radius of mulch did, however, act to lower soil temperatures and moderated large diurnal fluctuations in temperature throughout the growing season. In addition, a correlation was observed between organic matter content and soil bulk density, as well as organic matter content and soil pH after the first growing season. With the passing of time, positive improvements to these soil characteristics will hopefully be observed. The PRS™-Probes also proved to be a valuable means of measuring plant bioavailable nutrients in the soil. Soil chemical and physical conditions on the site should be monitored for several growing seasons so that longer temporally dependent alterations to soil may be observed. This longer timeframe will allow for potential changes in soil conditions to occur resulting from wood chip decomposition and subsequent incorporation into the soil surface layer. Organic mulch has been shown to improve some soil conditions in a short time period, such as moisture retention and soil temperature moderation; however, this study has concluded that potential improvements to several other soil conditions, resulting from the application of mulch, such as nutrient availability, bulk density, and compaction, require a longer period of investigation.

3.7 References

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CHAPTER 4

4.1 Limitations and Suggested Improvements

Site conditions were the major limitations of this study. Since the study area was accessible to the public, vandalism of some of the equipment occurred. During time period four, several of the PRS^{TM}-Probes were removed from the reference plots; therefore, four probes could not be combined together to produce an average nutrient supply rate for each of the trees. Additionally, one of the soil moisture logging stations was damaged during the CNE, which prevented the collection of data for time period five. Several of the permanent soil temperature probes were also damaged by water, although this was not a site-specific issue.

For future research on the site, it is recommended that the soil moisture logging stations be relocated closer to the trees to prevent vehicular damage (they were moved for the 2012 study season). Additionally, the placement of permanent soil moisture and soil temperature probes at the three reference trees without grass is important (this was also completed for 2012 data collection). PRS^{TM}-Probes are highly affected by soil moisture and soil temperature as ion movement and mineralization are greatly dependent on both of these soil properties. In the present study, insufficient soil moisture and temperature data (resulting from equipment damage and sensor failure) excluded these factors from being included as covariates in the ANCOVA model. It is important that future analyses prioritize inclusion of these factors so that a more robust explanation of the changes in nutrient supply rates overtime and among treatments can be provided.

Furthermore, soil cores should be taken again during the 2012 growing season to determine if soil pH, percent organic matter, bulk density, and salinity values have changed as the mulch continues to decompose. Investigation of several of these variables (i.e., pH and organic matter) once every 28 days, during the same time intervals as nutrient supply rate measurement, would also provide the potential for more detailed ANCOVA models. It is hypothesized that a higher temporal resolution for these covariates may provide a stronger explanation of differences in nutrient supply rates over the growing season compared to what was observed in this study.

Membrane contact with the soil is another issue that may have led to a reduction in the nutrient supply rates reported. Swelling and contracting of the soil occurs during wet and dry periods; therefore, it was important to ensure the soil was packed tightly around the resin membrane after insertion into the soil. The nutrient supply rates are measured based on total membrane surface area; thus, if there was incomplete soil contact with the probe, the surface area included in the calculation would have been inaccurate (Western Ag Innovations, 2010). During the drought period in July, it is possible that some of the PRS^{TM}-Probes located in the reference plots became detached from the soil. Additionally, competition from microbes and tree roots may have impacted nutrient supply rates.

A further limitation of this study was the small sample size. More replicates of each treatment type would allow for a stronger statistical analysis, especially since several nutrients were not normally distributed due to outliers in the data, and several covariates were not linearly related to the nutrient supply rates. Additionally, having at least three reference plots for each mulch radii (i.e., nine reference plots in total) would have provided greater statistical strength to the analysis. Despite this drawback, the results from this study are robust and do provide a tremendous understanding of the conditions experienced by each tree on this site. Since baseline conditions have been documented for each tree, this data can be compared to any future analyses conducted on the site. Changes in the soil chemical and physical factors can be measured each growing season to determine if soil conditions change overtime due to the application of the wood chips.

The small sample size was also limited by the discovery of concrete and other impervious material buried in the soil that prevented several trees from being included in the study. Even though mulch is expected to improve soil compaction and bulk density over the long-term, mulching cannot improve root penetration and nutrient and moisture retention if concrete pieces in the soil are blocking the direction where roots could otherwise grow. It is, therefore, recommended that any pieces of solid material observed near the soil surface be removed to improve the soil conditions necessary for healthy root growth.

4.2 Future Research

Overall, this project was part of a broader collaborative investigation of the potential benefits of mulch application to the soil rooting zone of newly planted trees. On the same study site, research was conducted examining the role of mulch in moderating near-surface soil temperatures, as well as the effect of slope on soil moisture content in relation to mulch treated and non-treated plots. Aerial photography has been taken to assess canopy cover and site specifications, and future studies will be conducted on soil compaction and soil structure. Combining the results from all experiments will allow for stronger conclusions to be drawn, which will provide a more in-depth understanding of the effect mulch has on the relationships between all the soil conditions necessary for tree health.

During the one-year time span of this experiment, the effects on tree growth and health were not observed; however, results from the soil physical and chemical tests can be compared to the optimal conditions necessary for tree health and survival, and extrapolations can be made. For instance, the cycling of nutrients and availability of these nutrients to tree roots is dependent on several chemical and physical soil factors, especially soil moisture and soil temperature. If optimal soil conditions can be achieved through the use of organic mulch, these improvements should be translated to tree health. Mauro (1997) found that the health of silver maple trees growing in downtown Montreal was positively correlated with P, K, and Ca concentrations, and negatively correlated with bulk density, Cu, and Zn. The author evaluated canopy percent dieback as a metric for evaluating tree health. In the present study, mulch increased soil P supply rates, and decreased Cu supply rates. Overtime, it is expected that mulch will also reduce bulk density and increase K and Ca supply rates.

Other studies have demonstrated a positive relationship between mulch application and tree growth and health. For instance, Litzow and Pellett (1983) reported a greater increase in percent trunk caliper (trunk diameter measured 15 cm (6”) from the ground) in green ash trees (*Fraxinus pennsylvanica* Marsh.) treated with hay and black plastic compared to non-mulched trees over three years. Wood chips and redwood bark mulch also demonstrated an increase in tree diameter; however, the improvement was not as great. Additionally, Green and Watson (1989) reported increases in trunk caliper, crown development, and root development in Green Mountain sugar maples treated with composted leaves and wood chips five years after planting. Compared to non-mulched trees (surrounded by turf), the crown of mulched trees were almost twice the size, trunk diameter increases were approximately three times larger, and root density was significantly higher. Based on the results from these studies, it is expected that the enrichment of the soil conditions at the Exhibition Place study site will be translated into noticeable improvements to tree health and growth within the next few growing seasons.

Using the baseline conditions collected for the site, further research may be able to examine the effects of different mulch areal treatments on tree growth. Tree diameters were measured in the first season and can be measured continuously to determine if trees applied with mulch and different radii of mulch have faster growth rates than those without. Tree cores can also be taken to support this hypothesis. Additionally, further aerial imagery of the site can allow for changes in tree canopy cover to be observed over time when compared to pictures taken in the first year of the study. When testing the connection between mulching and tree health or growth, it is important to consider the type of tree species being analyzed. In this study, a variety of tree species were included due to site constraints. Since the research aimed to determine the effect of mulch on soil chemical and physical characteristics, rather than directly on species-specific tree health, having different tree species was not considered a limitation. However, future researchers may want to consider including only one tree species or tree species from the same genus in their analysis when testing for direct or indirect effects of mulch on tree growth or health. This is because different species have different nutrient requirements, as well as different levels of tolerance for soil compaction, pH, moisture content, and soil temperature. At this study site, there were several silver maple and sugar maple trees that were subjected to different treatments, which could be used as a comparison to determine differences among trees. The results, however, would likely be anecdotal and not statistically robust due to the small sample size.

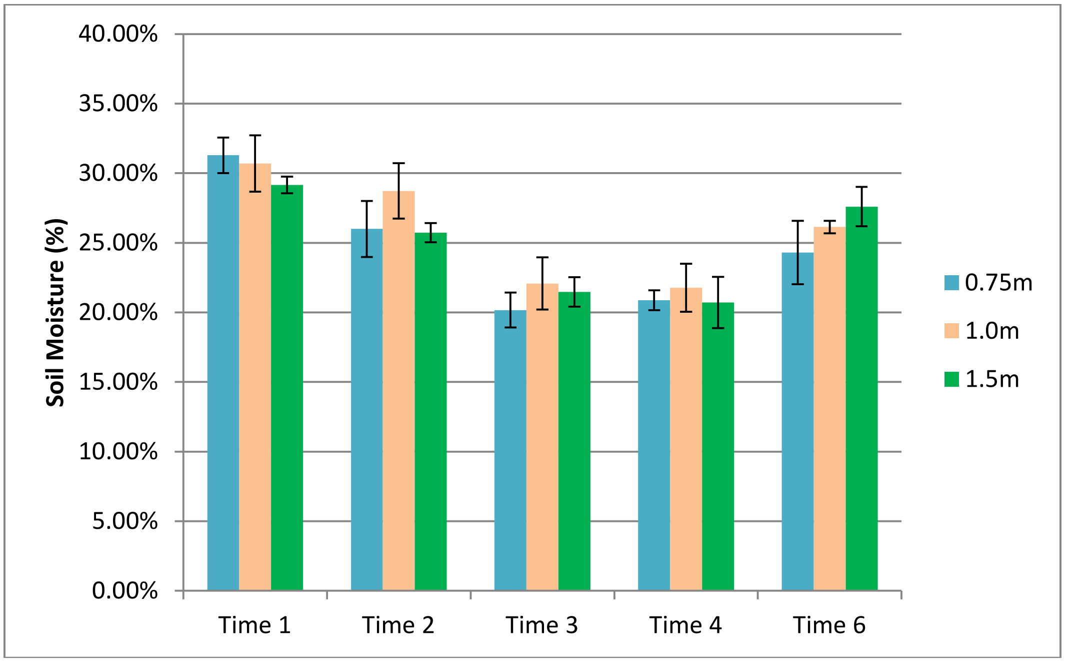
In terms of nutrient availability, results from the present study can be used to develop nutrient management strategies for newly planted urban trees. Future experiments can be conducted to examine whether wood chips mixed with compost may have further benefits for trees planted in soils that are nutrient-limited. Temporal changes in nutrient availability over the growing season may prompt studies to examine the optimal time to apply mulch. Application of fertilizer to the soil is another option for increasing deficient nutrient concentrations; however, fertilizers can be expensive, often applied improperly, and can lead to plant dependence on artificial inputs (e.g., high N fertilizers).

A more natural option for increasing nutrient absorption is to inoculate tree roots with mycorrhizal fungi. This practice has been undertaken in municipal nurseries in Montreal that transplant trees in the downtown area (Mauro, 1997). These mycorrhizal fungi form a symbiotic relationship with their host tree – the fungi produce a network of hyphae on the root hairs and short root branches, which allows for increased nutrient and water absorption. In turn, the tree provides the fungi with carbon derived from photosynthesis (Craul, 1992; Roberts *et al*., 2006). Many trees are naturally colonized by mycorrhizae. For example, in Montreal, approximately 45 percent of silver maple street trees were reported to be naturally colonized with vesicular-arbuscular mycorrhizae (VAM) in 1997 (Mauro, 1997). However, any stress that reduces plant photosynthesis, such as poor soil conditions, will likely reduce or inhibit the presence of these fungi (Craul, 1992; Mauro, 1997). In some instances, up to 15 percent of net primary production is devoted to supporting mycorrhizal biomass; thus, trees growing in unfavourable conditions often cannot support colonization (Roberts *et al*., 2006). Since the application of organic mulch is known to improve soil conditions, inoculating tree roots in conjunction with the use of wood chips, may provide further benefits to the tree in terms of nutrient and water acquisition. Several studies have reported increased uptakes of N, P, K, and S due to mycorrhizal symbiosis (Rhodes and Gerdemann, 1978; Rygiewicz *et al*., 1984; Li *et al*., 1991; Mauro, 1997). Prior to inoculation, it is important to test whether or not the tree roots are already colonized by mycorrhizae. If they are not, choosing the right type of fungi is also essential, since some tree species respond more favourably to certain strains than others (Roberts *et al*., 2006).

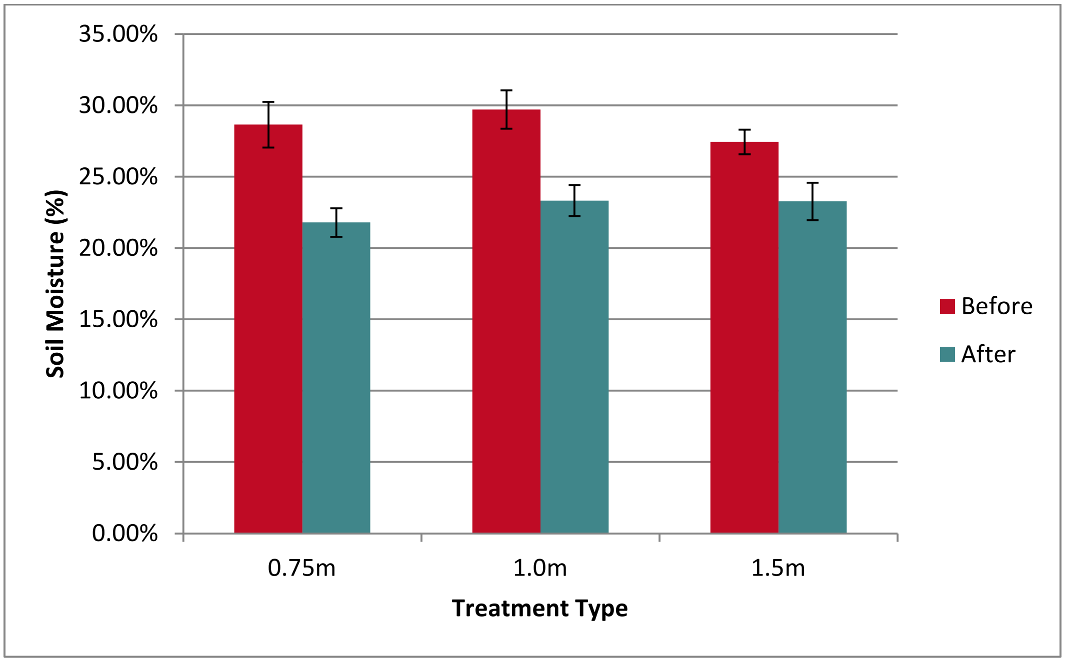
Furthermore, improving nutrient bioavailability to the trees located on this study site may be augmented with irrigation. During the sample period, the sprinklers located on the property were turned off because the study aimed to achieve natural site conditions (i.e., precipitation accumulation that would be observed in most treed urban parks). Also, the main focus of the study was to determine if there was a correlation between mulching and nutrient acquisition – if the sprinklers had been turned on, it would have been difficult to delineate changes in nutrient supply rates to increased water availability or to the application of mulch. Instead, all plots received the same level of water determined by the amount of precipitation that fell on the site. However, now that baseline conditions have been collected, allowing the sprinklers to be turned on will likely lead to improved nutrient supply rates, since the presence of water enables nutrients to be transported toward root surfaces. Also, if the soil moisture probes work successfully in the next growing season, changes in soil moisture content between trees can be accounted for in the ANCOVA model. A study by Kumar and Dey (2011) reported several improvements to soils treated with inorganic mulch (polyethene film) and organic mulch (hay) along with either drip or surface irrigation compared to non-treated plots. These improvements included: increased root growth, greater minimum and lower maximum soil temperatures, and a higher uptake of N, P, and K determined by dried plant and root samples. Since the amount of precipitation that fell over the site during the present study was sporadic and low during some time periods, applying water through irrigation will help to improve the soil conditions necessary for tree health and growth.

Overall, improving the soil conditions for newly planted urban trees is vital if these trees are to survive beyond the crucial two to five years after planting. Mature trees have many more environmental benefits due to their larger canopy size than young trees; therefore, ensuring the long-term survival of trees in urban areas is of great importance. The results gathered from this study may also benefit the City of Toronto in the pursuit of its goal to increase the citywide tree canopy to 30-40 percent by 2050. Knowledge arising from this research can be used to improve urban forest management strategies by providing a more in-depth understanding of the prescriptive use of organic mulch for improving soil conditions necessary for the long-term health and survival of urban trees.

Appendix A: Soil Moisture

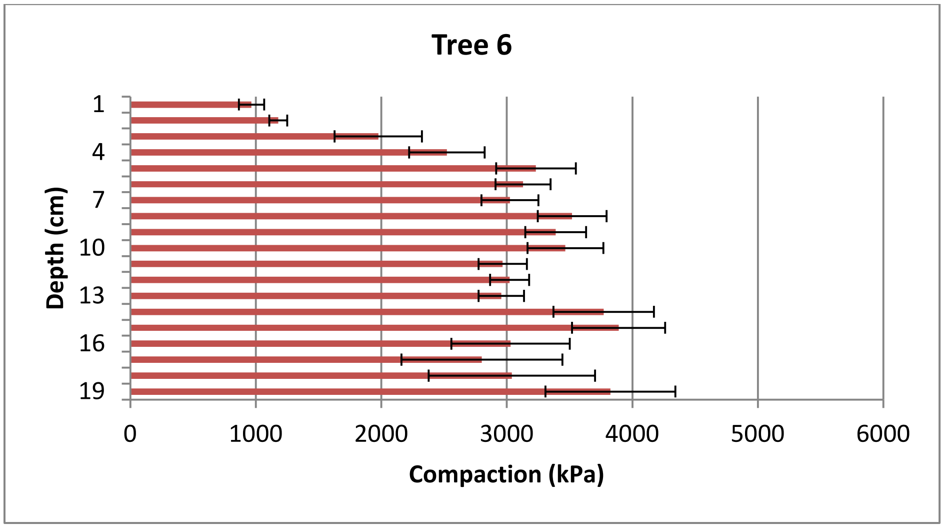


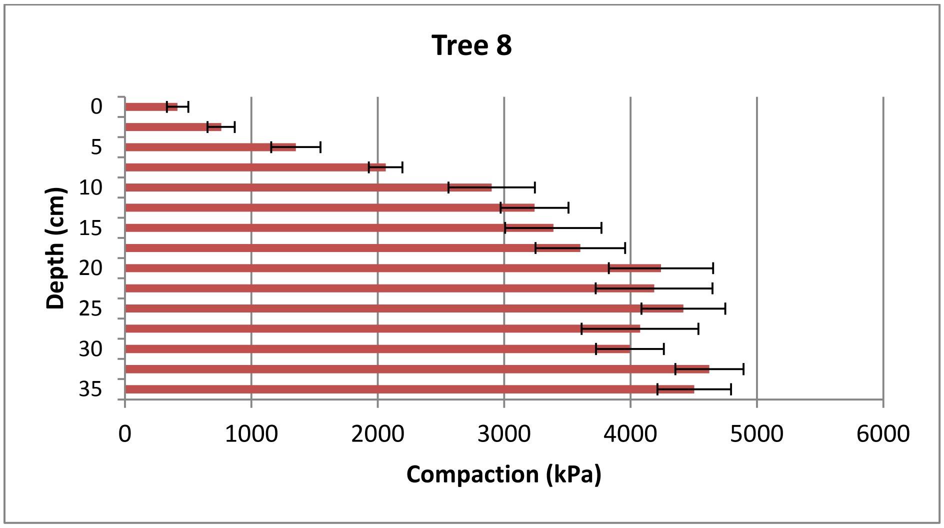
Average soil moisture (%) for each treatment type over the sample period with standard error

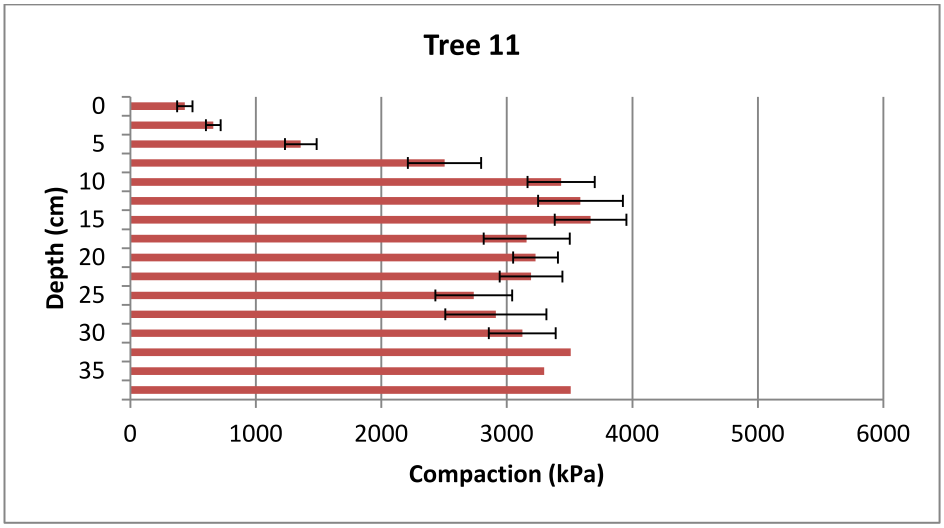


Average soil moisture (%) before and after mulch application for each treatment type with standard error

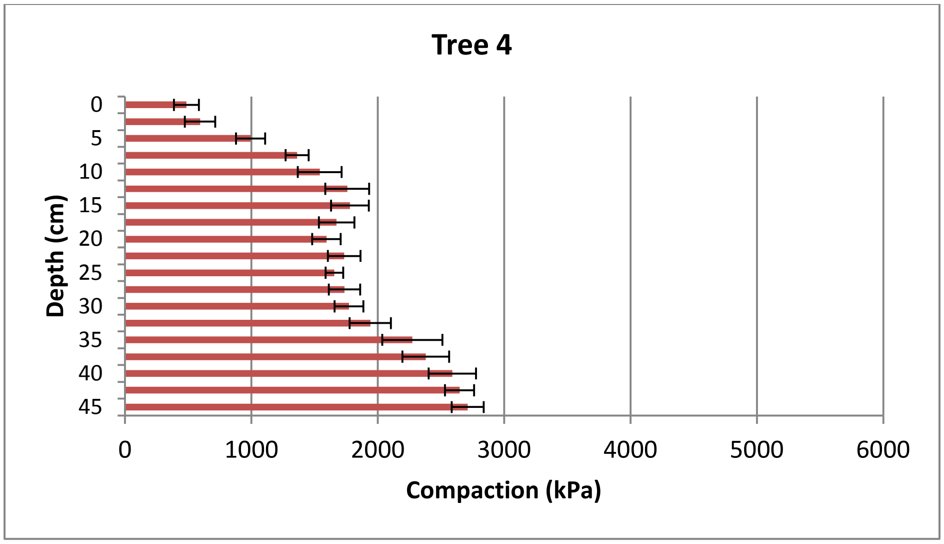
Appendix B: Soil Compaction

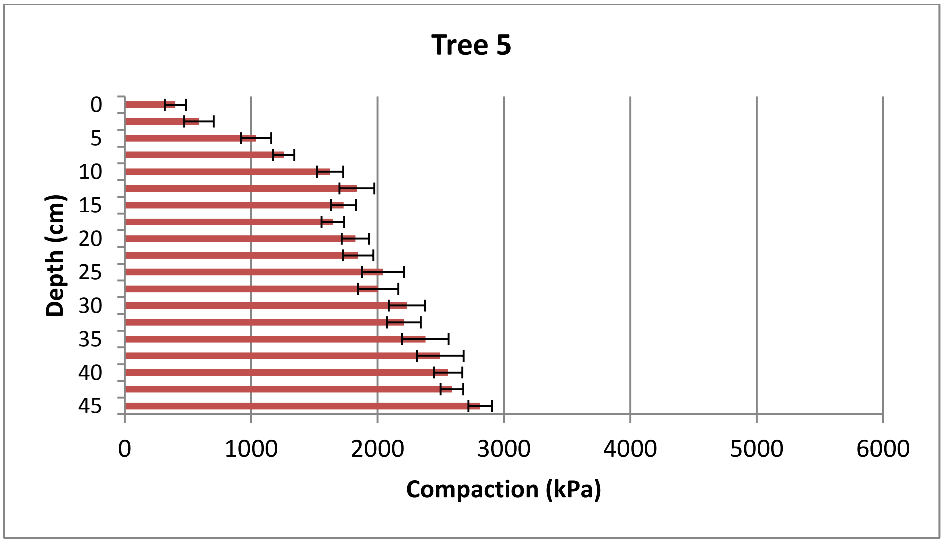


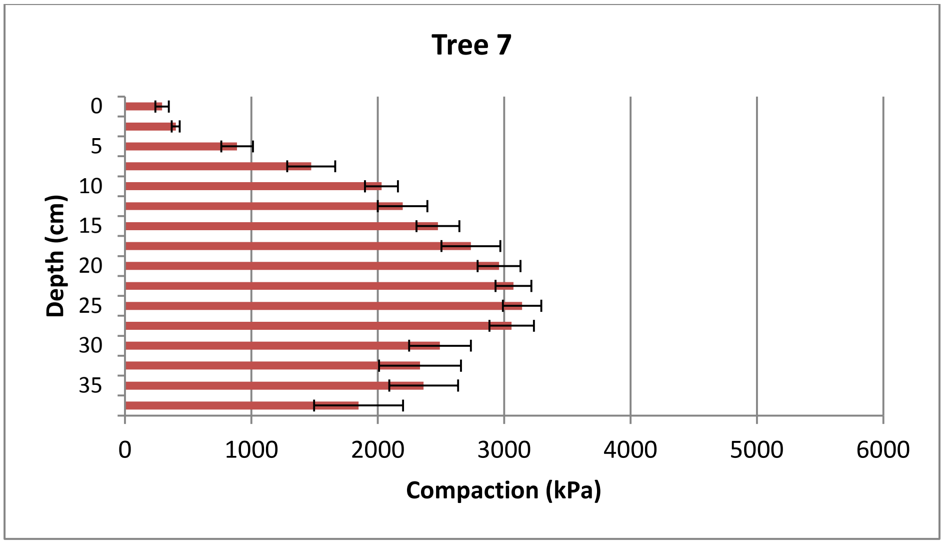




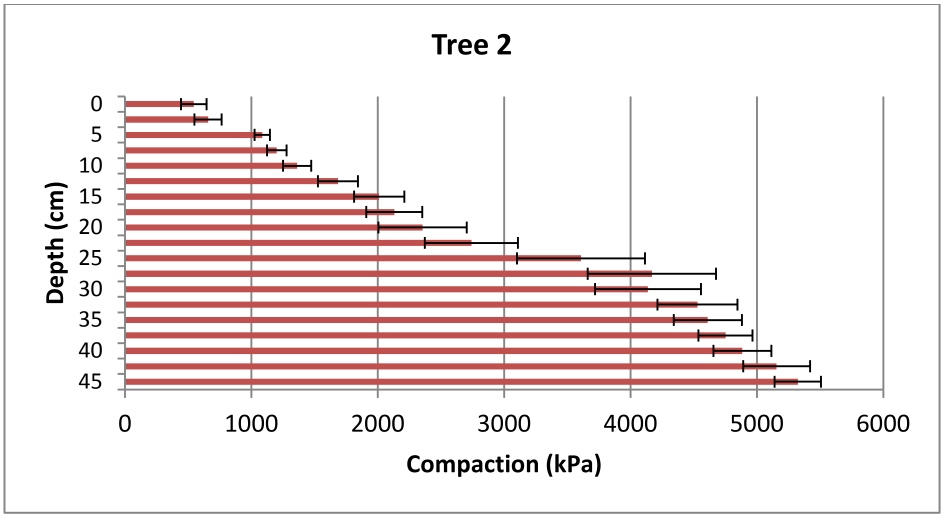
Average soil compaction (kPa) (0-45 cm in depth) for 0.75 m treatment plots

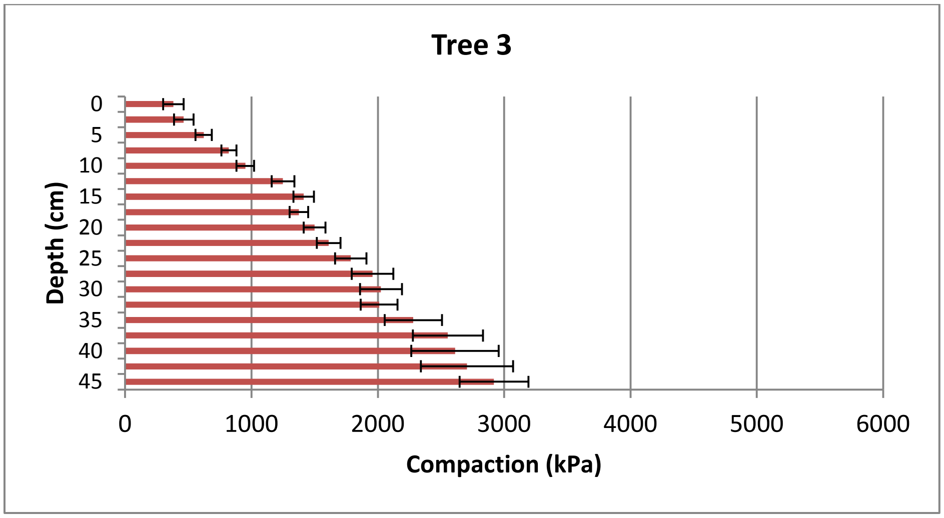


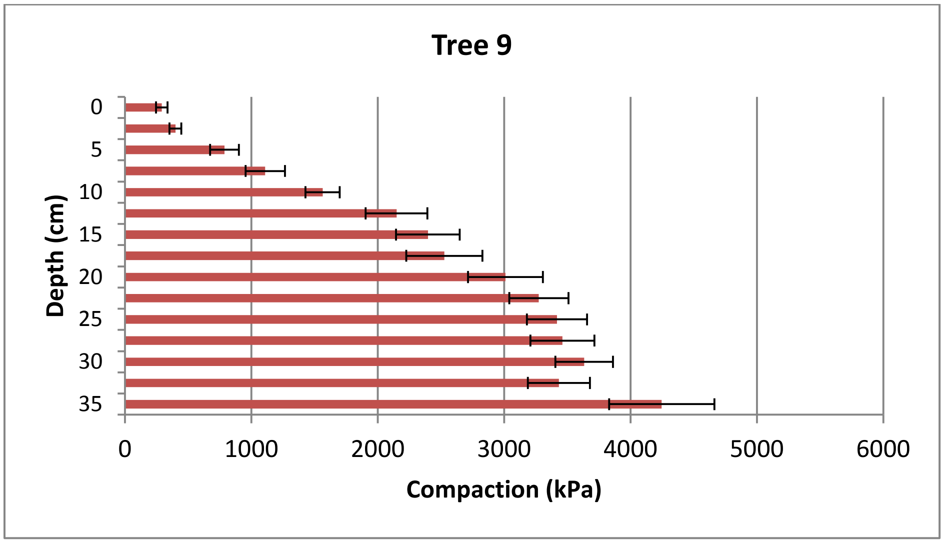




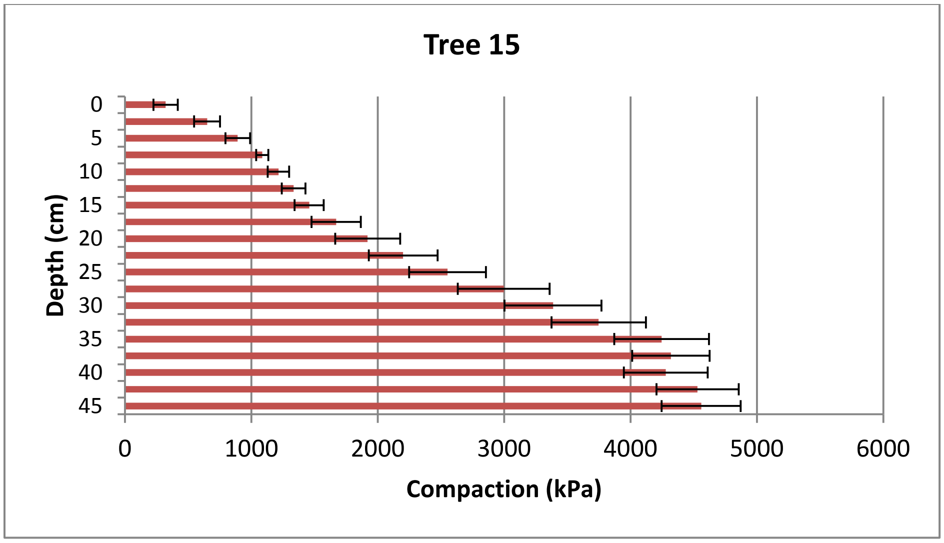
Average soil compaction (kPa) (0-45 cm in depth) for 1.0 m treatment plots

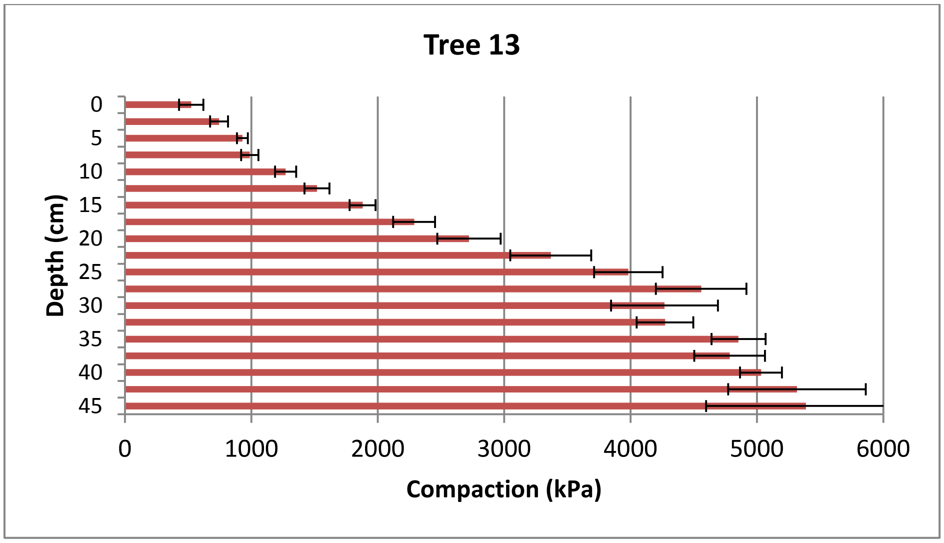


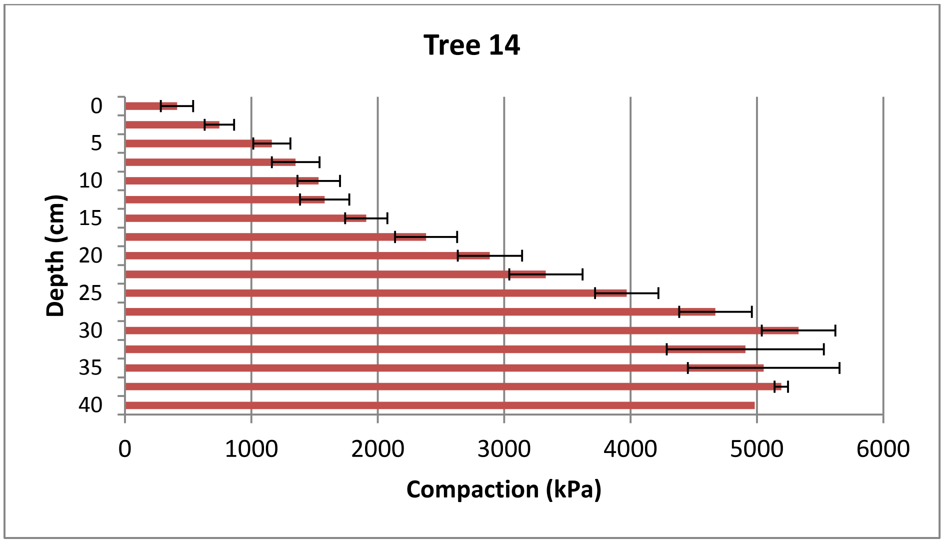




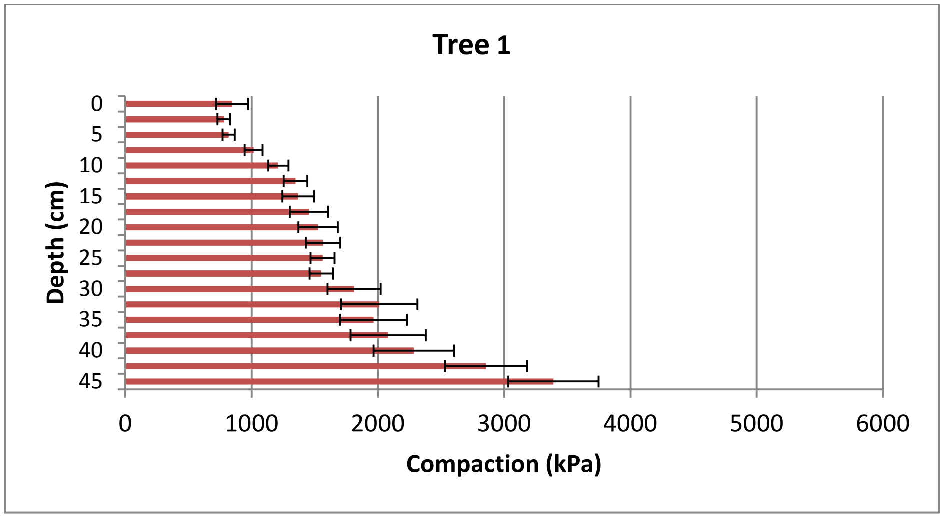
Average soil compaction (kPa) (0-45 cm in depth) for 1.5 m treatment plots

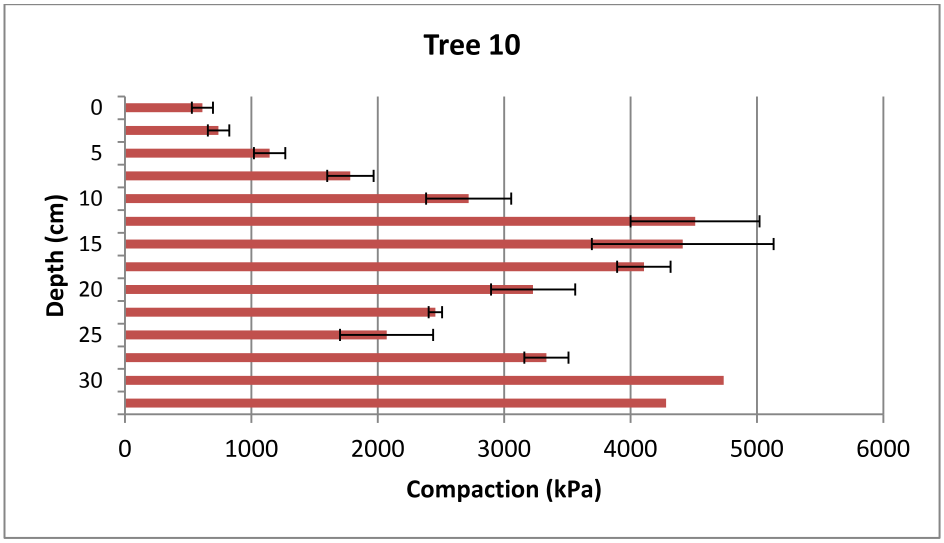


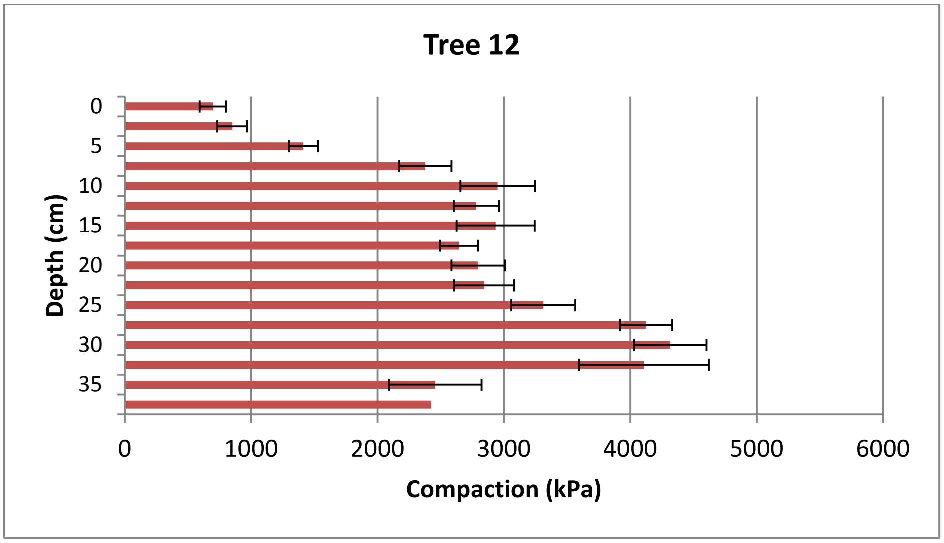




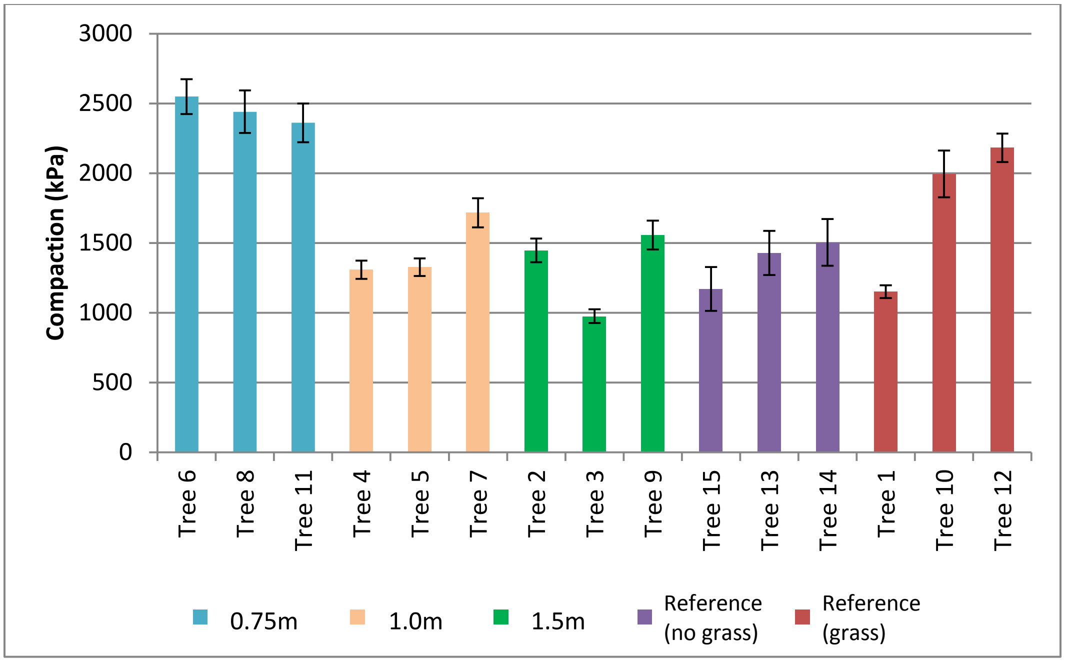
Average soil compaction (kPa) (0-45 cm in depth) for reference plots without grass



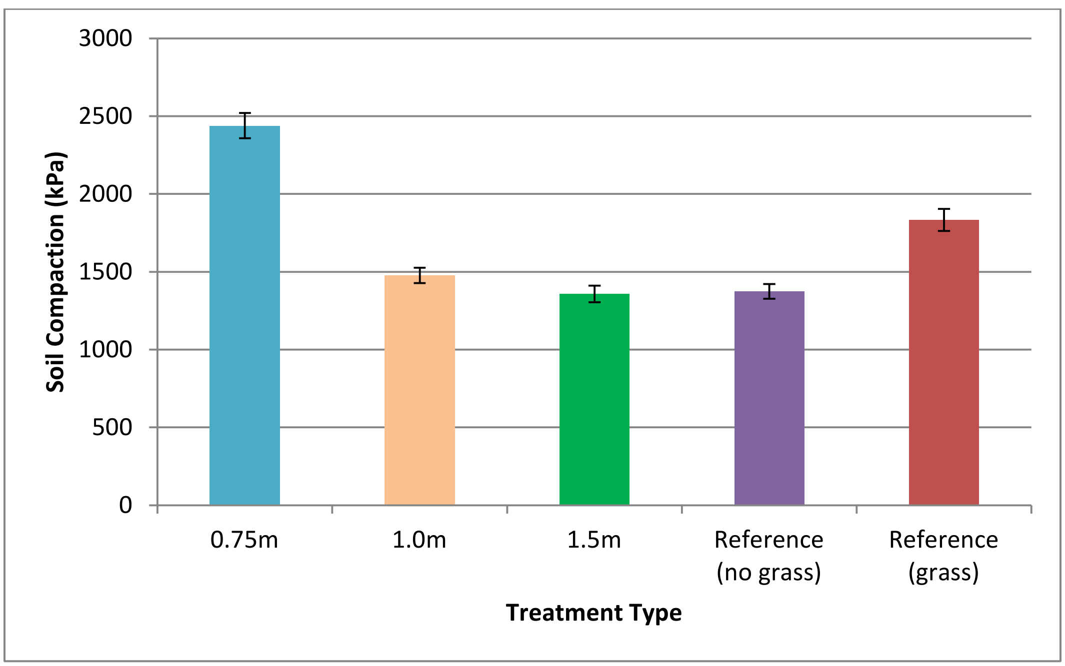




Average soil compaction (kPa) (0-45 cm in depth) for reference plots with grass

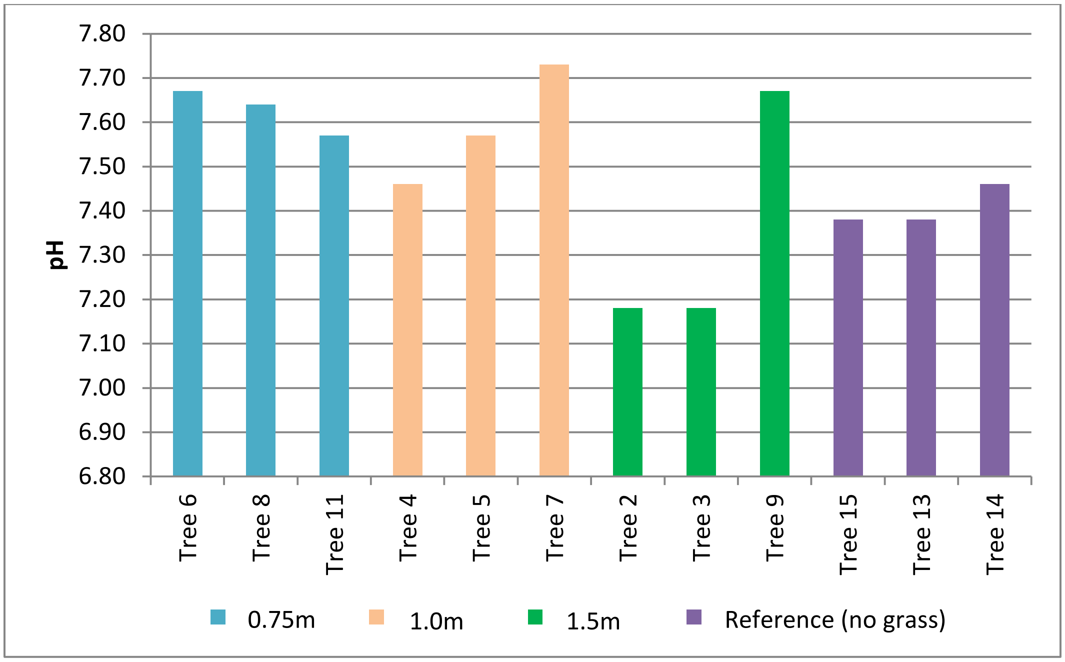


Average soil compaction (kPa) (0-20 cm in depth) for each tree with standard error

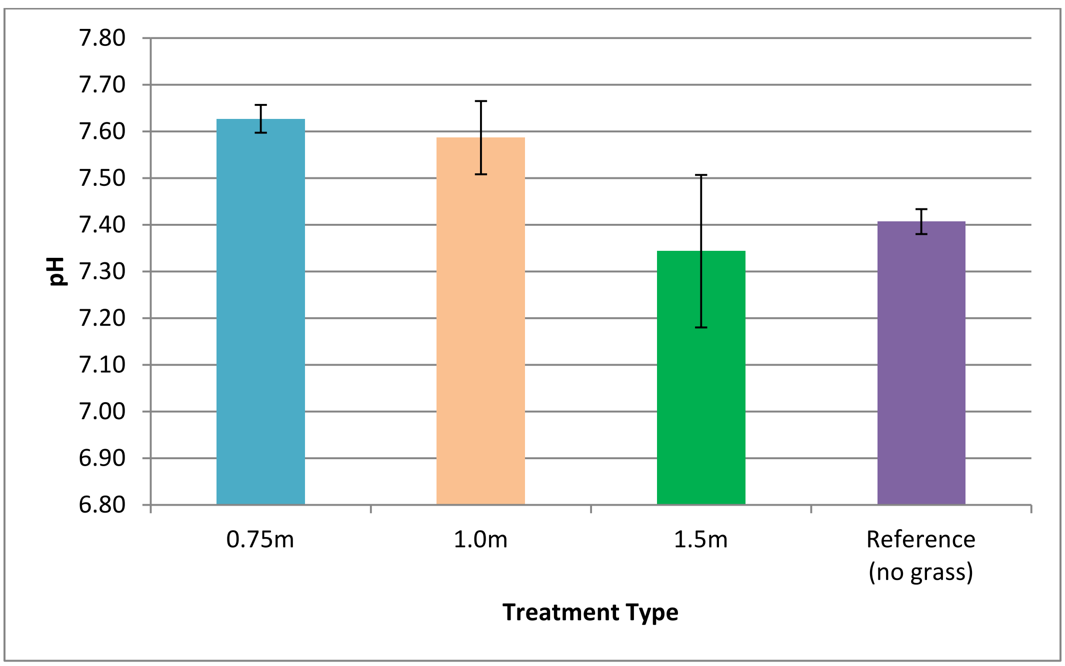


Average soil compaction (kPa) (0-20 cm in depth) for each treatment type with standard error

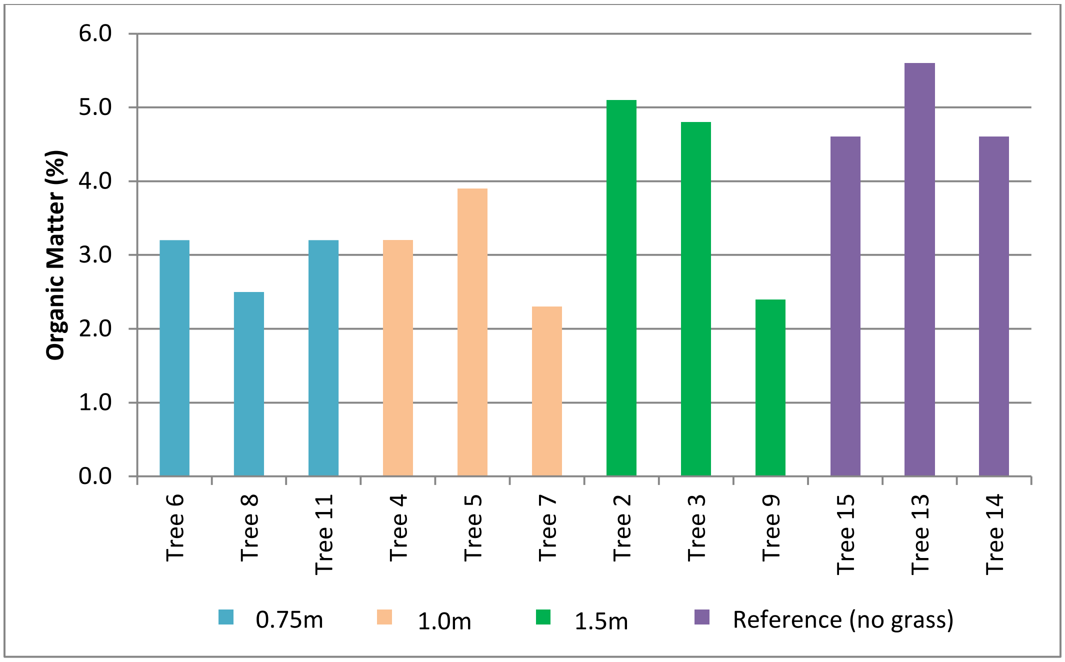
Appendix C: Other Soil Chemical and Physical Factors



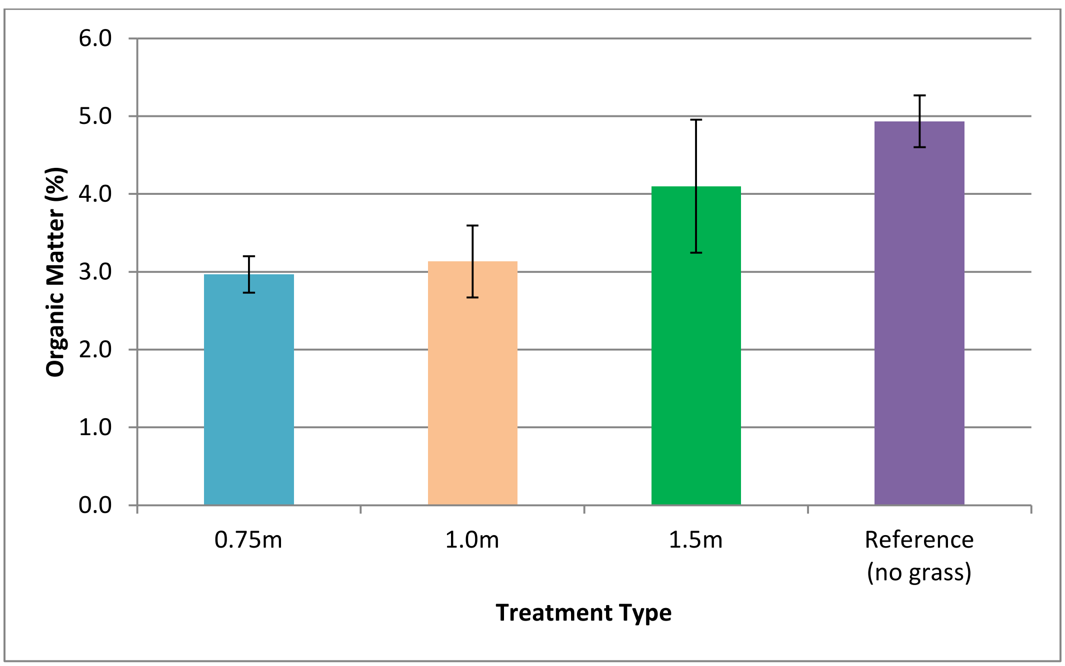
Soil pH for each tree



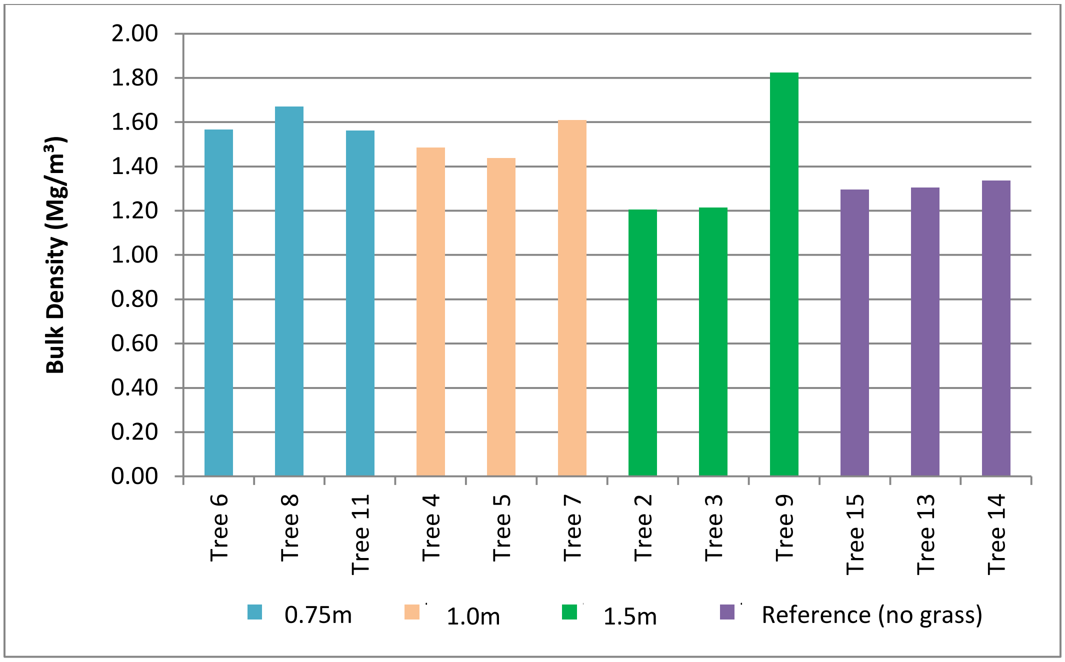
Average soil pH for each treatment type with standard error



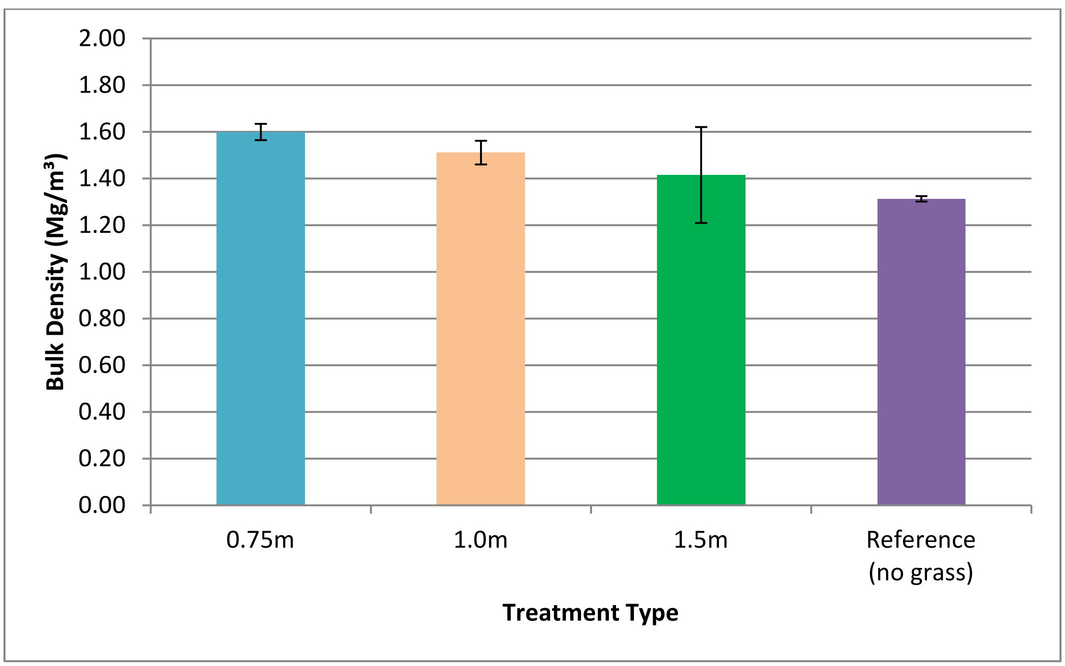
Percent organic matter for each tree



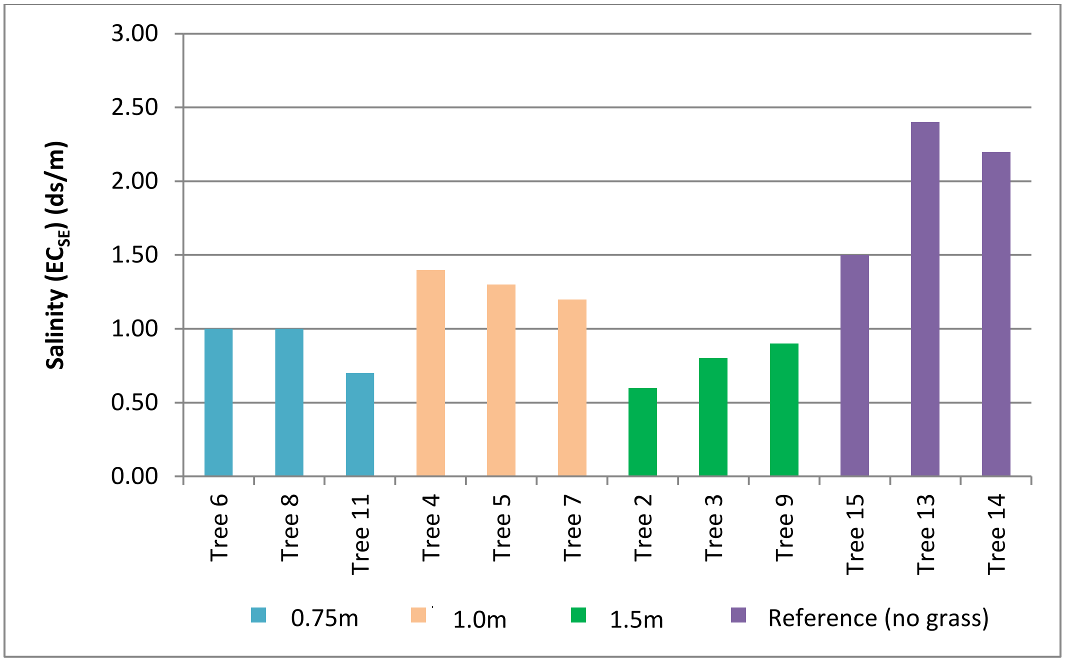
Average percent organic matter for each treatment type with standard error



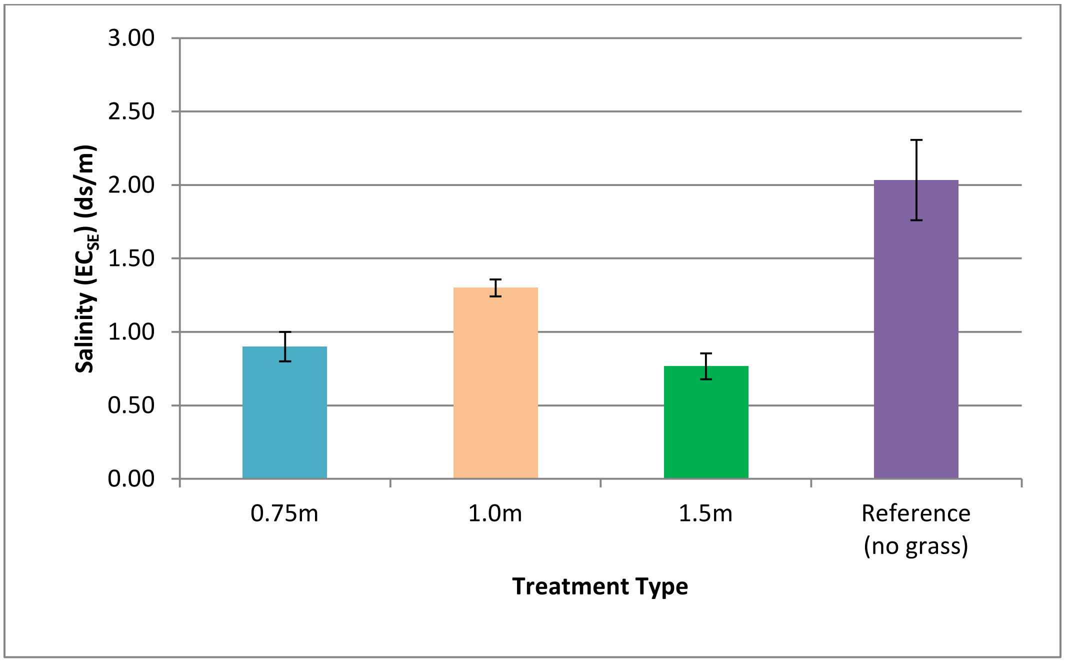
Bulk density (Mg/m^3) for each tree



Average bulk density (Mg/m^3) for each treatment type with standard error

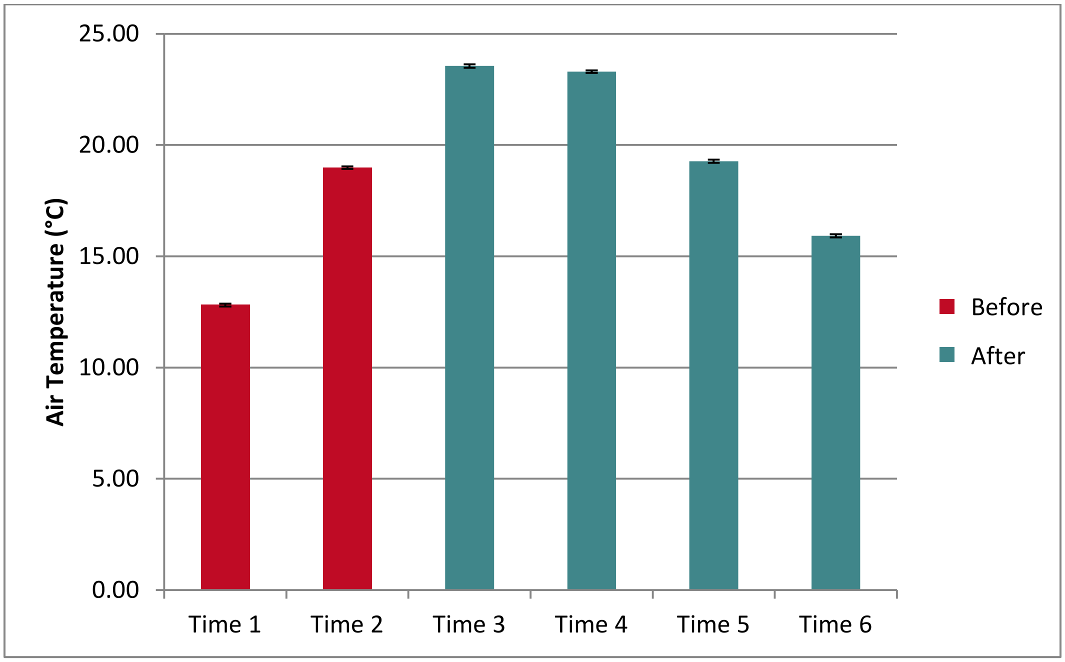


Salinity (EC$_{SE}$) (ds/m) for each tree

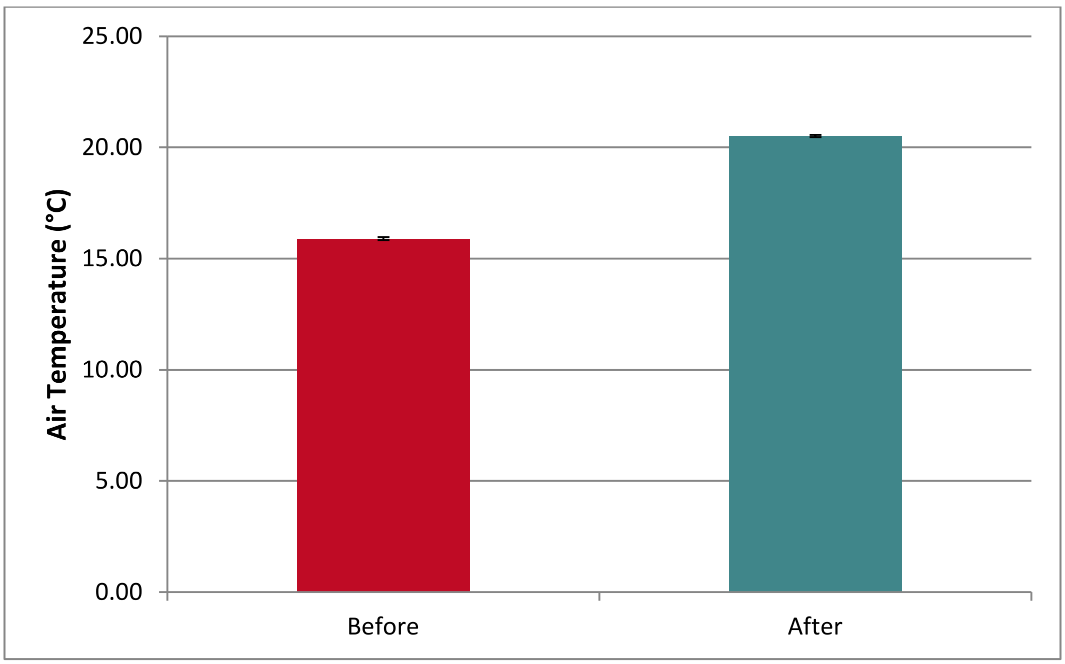


Average salinity for (EC$_{SE}$) (ds/m) each treatment type with standard error

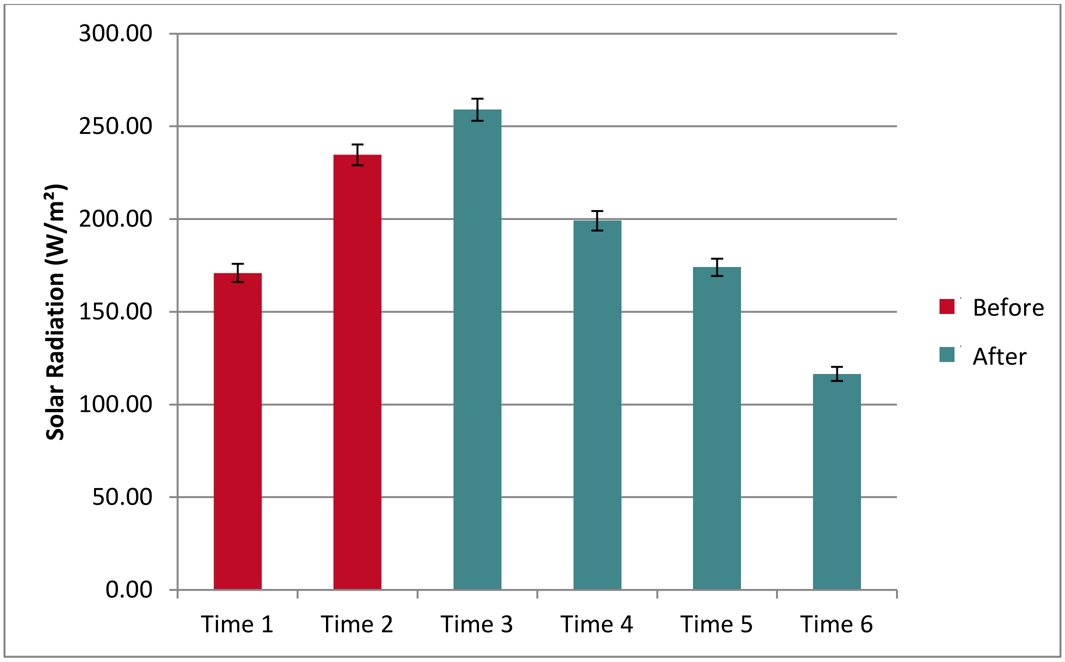
Appendix D: Meteorological Data



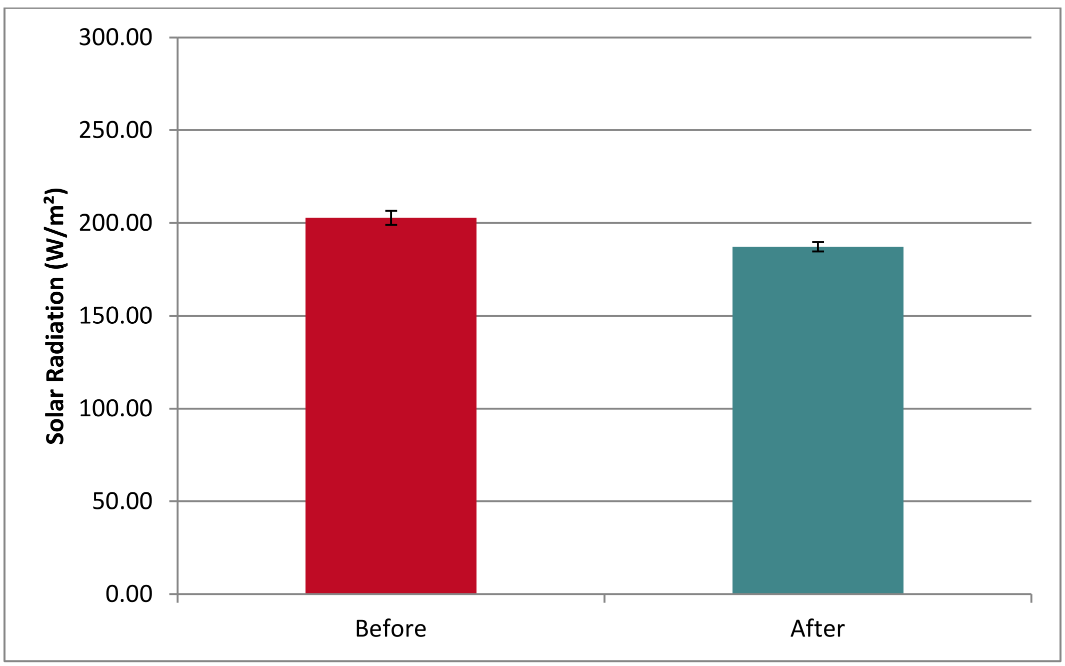
Average air temperature (°C) for each time period with standard error



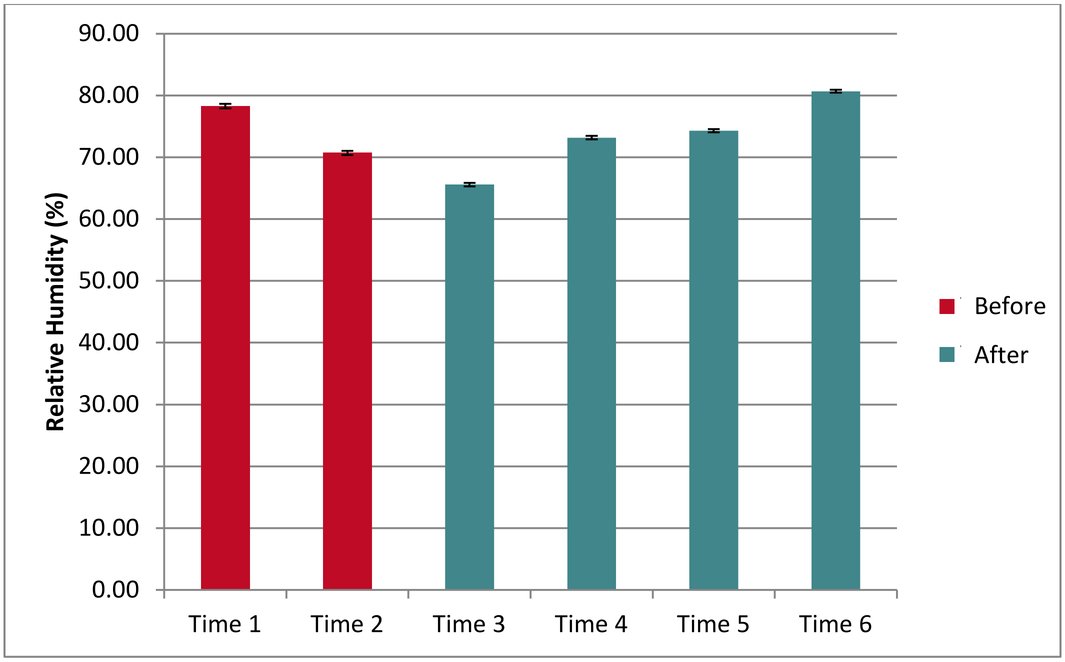
Average air temperature (°C) before versus after mulch application with standard error



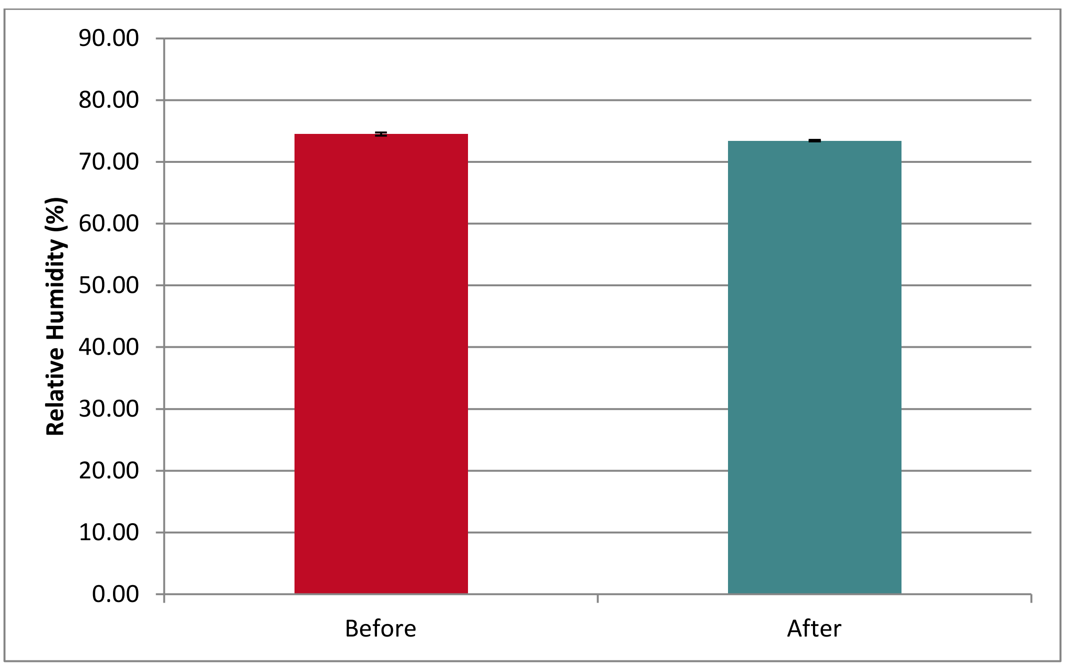
Average solar radiation (W/m^2) for each time period with standard error



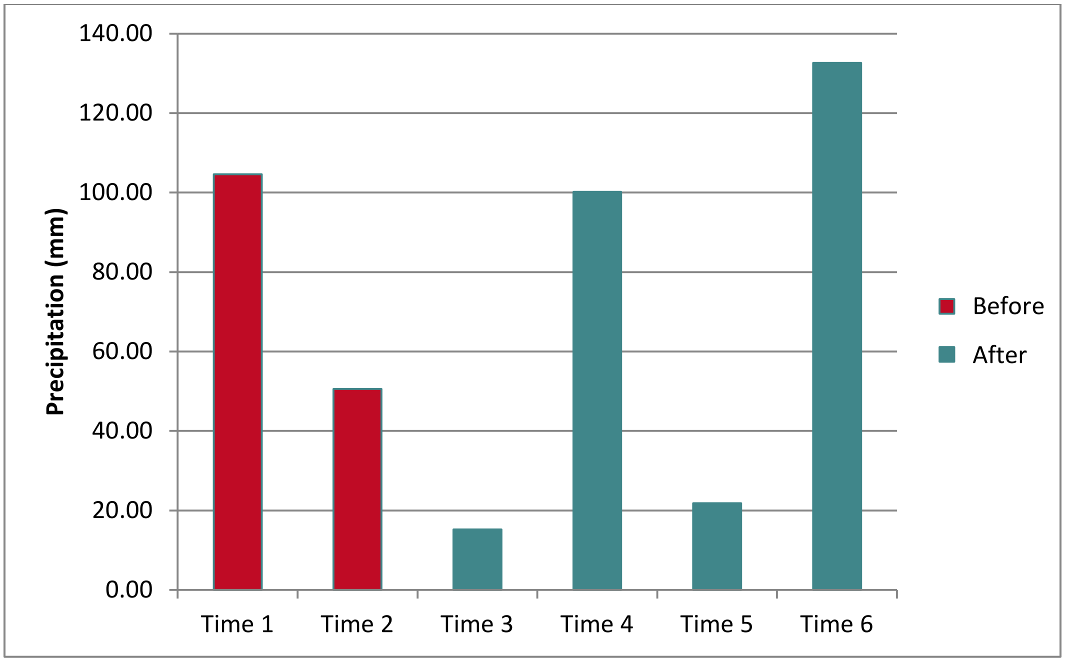
Average solar radiation (W/m^2) before versus after mulch application with standard error



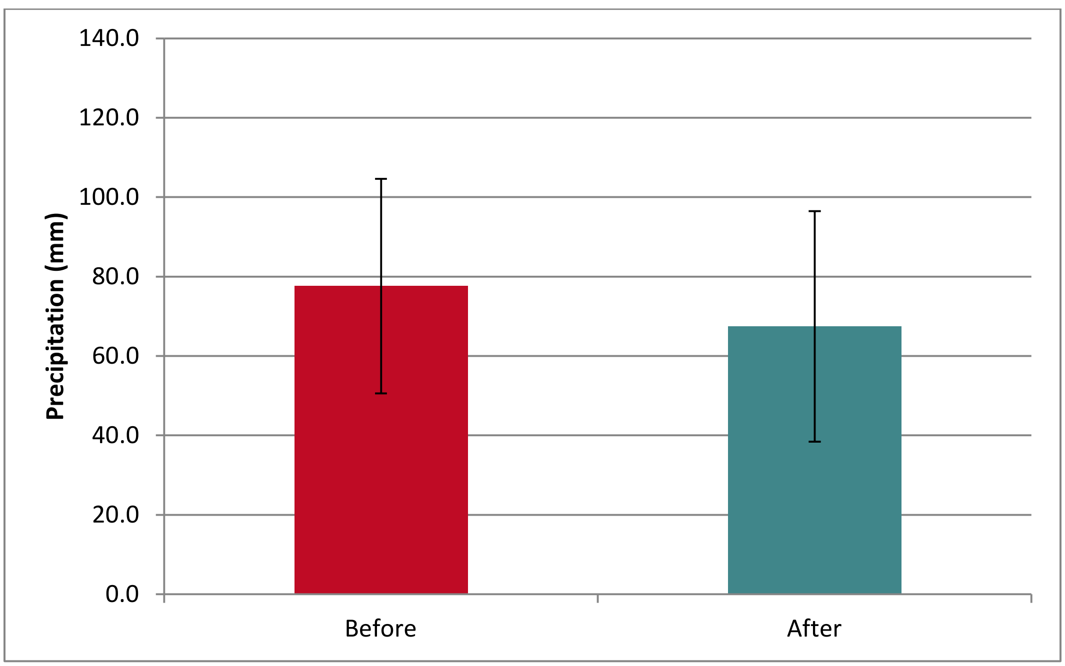
Average relative humidity (%) for each time period with standard error



Average relative humidity (%) before versus after mulch application with standard error



Total precipitation (mm) during each time period



Average total precipitation (mm) before versus after mulch application with standard error

Appendix E: Nutrient supply rates (μg/10cm^2/28 days) for each time period (raw data from Western Ag Innovations)

Tree	Time Period	NO3	NH4	P	K	S	Ca	Mg	Cu
6 (0.75 m)	1	1.8	4.0	3.0	22.6	186.6	2830.0	169.4	8.6
	2	1.8	0.0	5.6	73.4	16.4	2172.0	167.2	2.2
	3	6.6	9.0	3.8	198.6	6.8	1269.2	116.0	0.5
	4	6.0	1.2	18.4	334.6	18.9	2456.0	210.8	1.9
	5	0.0	0.8	2.2	114.8	6.3	636.4	65.5	0.1
	6	1.0	0.2	28.9	103.4	62.2	2652.0	155.5	2.6
8 (0.75 m)	1	2.4	6.0	4.0	34.4	407.0	2870.0	161.8	9.8
	2	9.2	0.0	5.8	109.4	59.8	2134.0	149.6	1.6
	3	5.1	4.1	8.4	207.2	19.6	955.4	84.9	0.6
	4	8.6	0.3	26.7	383.4	41.3	2390.4	198.5	1.1
	5	2.4	139.0	7.4	310.4	11.7	1324.6	117.2	0.4
	6	14.5	0.0	27.7	79.2	175.9	2910.0	174.8	3.4
11 (0.75 m)	1	4.8	9.2	3.2	32.4	191.0	3250.0	202.0	6.4
	2	15.8	0.0	3.6	28.6	60.2	2646.0	171.8	3.4
	3	2.7	5.2	7.9	343.0	12.7	1787.0	154.5	0.6
	4	20.4	0.4	27.1	59.6	35.4	3392.7	236.8	1.3
	5	5.5	1.7	5.7	67.6	32.0	2108.0	150.7	1.3
	6	4.2	0.4	12.3	33.0	40.7	2678.0	172.5	3.4
4 (1.0 m)	1	2.2	2.2	2.0	21.4	119.4	2588.0	175.8	5.0
	2	4.8	0.0	4.8	45.4	50.6	2454.0	171.8	2.2
	3	10.0	7.3	8.4	222.6	15.7	924.2	96.8	0.2
	4	10.9	1.6	22.4	249.8	27.4	1538.3	141.5	0.7
	5	8.7	0.0	4.0	119.6	15.4	1112.8	105.2	0.2
	6	17.9	0.0	10.4	34.9	123.0	2790.0	185.4	1.7
5 (1.0 m)	1	1.0	2.8	9.4	16.0	43.0	2592.0	157.4	1.4
	2	13.8	0.0	7.6	56.6	56.6	2640.0	168.4	2.2
	3	9.9	9.7	5.1	105.4	8.9	967.4	85.3	0.2
	4	3.6	0.0	36.4	296.4	29.6	1849.0	147.0	0.6
	5	2.1	3.5	12.4	123.4	8.5	687.8	59.1	0.1
	6	14.3	0.1	17.4	100.7	127.5	2600.0	147.3	5.9
7 (1.0 m)	1	1.6	7.0	2.4	25.0	154.0	2704.0	158.0	5.8
	2	7.4	0.0	4.2	32.8	119.0	2426.0	161.6	2.0
	3	3.7	9.6	5.3	110.2	20.4	1893.6	157.2	0.6
	4	3.8	0.0	19.8	117.6	77.0	1948.6	140.1	2.0
	5	4.3	0.3	3.3	41.9	21.4	1251.6	86.2	0.7
	6	4.2	0.4	8.8	38.6	247.2	2724.0	163.1	6.1

Tree	Time Period	NO3	NH4	P	K	S	Ca	Mg	Cu
2 (1.5 m)	1	15.4	0.0	1.6	29.0	12.2	2754.0	187.8	8.0
	2	13.4	0.0	3.6	98.6	8.0	2580.0	215.8	2.2
	3	7.9	3.0	12.5	343.8	5.4	1488.4	154.7	0.4
	4	7.2	1.6	31.8	741.4	14.6	2094.0	226.2	1.3
	5	4.9	1.7	9.1	182.8	12.9	1183.2	114.6	0.3
	6	5.9	1.2	10.1	97.1	65.5	2808.0	221.4	4.6
3 (1.5 m)	1	15.2	5.8	3.2	33.6	19.4	3246.0	222.4	2.6
	2	24.2	0.0	4.6	121.6	14.8	2514.0	190.6	2.4
	3	16.9	5.0	4.7	138.0	4.5	1172.6	108.0	0.1
	4	39.9	0.0	24.8	197.2	22.4	1789.0	157.6	1.2
	5	69.2	1.5	6.0	83.8	16.0	1735.4	156.7	0.7
	6	22.1	0.0	8.0	46.3	62.0	3016.0	225.6	5.6
9 (1.5 m)	1	1.8	4.8	3.0	25.0	373.2	2622.0	164.4	3.2
	2	4.8	0.0	2.6	24.2	233.6	2620.0	153.4	4.4
	3	7.2	6.2	6.3	92.2	30.5	1362.4	108.8	0.7
	4	2.7	2.1	18.7	214.8	119.2	2502.0	177.8	1.5
	5	1.0	0.7	1.6	51.2	26.2	810.8	75.4	0.5
	6	0.0	0.0	9.8	35.7	263.0	2548.0	142.2	3.0
15 (0.75 m reference)	1	2.8	0.0	3.0	32.0	13.6	3180.0	140.4	5.0
	2	13.6	0.0	5.4	188.8	3.4	2422.0	122.8	2.6
	3	11.7	7.4	9.6	723.0	9.2	1165.2	100.1	0.2
	4	103.2	2.3	6.1	98.6	22.7	3423.0	156.8	1.1
	5	13.0	0.9	1.3	66.6	4.8	1450.8	86.6	0.2
	6	215.4	0.3	6.8	32.7	193.3	3464.0	151.7	3.5
13 (1.0 m reference)	1	1.0	3.8	7.6	23.6	211.8	2638.0	211.6	1.8
	2	5.6	0.0	7.2	40.2	131.4	2344.0	195.6	2.8
	3	5.6	5.2	4.6	113.7	13.4	850.6	87.6	0.2
	4	67.1	1.0	10.0	46.4	60.2	1850.0	185.5	1.3
	5	21.5	0.9	2.9	32.1	9.4	697.9	67.8	0.2
	6	316.4	0.0	9.2	17.3	207.2	2852.0	182.8	9.2
14 (1.5 m reference)	1	24.0	4.6	3.6	28.4	79.4	2888.0	159.4	11.6
	2	25.4	0.0	11.4	67.2	32.4	3100.0	170.6	5.8
	3	28.9	5.7	21.6	141.6	27.6	1440.6	114.1	0.6
	4	419.2	0.8	16.0	49.0	39.4	2472.0	151.4	1.6
	5	327.7	1.5	5.7	77.5	47.3	2356.7	137.2	1.0
	6	932.1	0.9	6.0	33.0	159.5	2508.0	152.1	4.0

Appendix F: Supplementary description of PRS^{TM}-probes

Adsorption of ions to PRS^{TM}-probes

When first inserted into the soil, the flux of ions to the membrane of the PRS^{TM}-probe is not selective to a certain ion type; it is dependent on the presence and activity of the ions in the soil and the diffusive resistance. However, as the burial period continues, certain ions are favoured over others. For instance, ions with a higher valence are held more strongly to the membrane than ions with a lower valence (i.e., $Al^{+3} > Ca^{+2} > K^{+}$). Additionally, the ability of ions to bind to cation-exchange groups in the soil will affect their adsorption; Cu is held strongly to soil particles, which means that the adsorption of Cu to the probe membrane will reach a plateau depending on the relative strength of the soil. On the other hand, NO_3^- is weakly held by soil particles, resulting in an adsorption of NO_3^- to the probe membrane that increases linearly with time. Despite this, the PRS^{TM}-probes are a valuable resource and provide a dynamic measure of ion flux in the soil overtime, which conventional methods of extraction are unable to accomplish.

Comparison between ion exchange resins, conventional extraction methods, and tissue analysis

The unit of measurement for the PRS^{TM}-probes (µg nutrient/10cm^2 ion-exchange membrane surface area/time of burial) is unique from the units reported in conventional methods of nutrient extraction and cannot be directly compared. However, similar linear trends have been observed between ion exchange resins, conventional methods, and tissue analysis. Despite this, it is still inaccurate to make the assumption that these reported linear trends are similar for all ions and for all soil conditions. Although close relationships do occur between different methods of measurement, these relationships are not universal because they take into account different variables that are dependent on time and space. For instance, conventional extraction methods measure nutrients in the soil solution and in the solid-phase at one particular time and location.

PRS^{TM}-probes act very similar to plant roots and measure bioavailable nutrients over a certain burial time, which is dependent on soil conditions and ion characteristics. Tissue analysis measures plant uptake of ions from the soil and is dependent on the growth period, root system, nutrient uptake mechanism of the plant, and the soil conditions. Therefore, although positive correlations have been made between different nutrient extraction methods, there is no simple relationship or conversion factor between these methods that is valid for all conditions and all nutrients.

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