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The Management of Tree Root Systems in Urban and Suburban Settings: A Review of Soil Influence on Root Growth

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Abstract. The physical, chemical, and biological constraints of urban soils often pose limitations for the growth of tree roots. An understanding of the interrelationships of soil properties is important for proper management. As a result of the interdependence of soil properties, the status of one soil factor can have an effect on all others. Preventing soil damage is most effective and preferred. Cultural practices, such as cultivation and mulching, can be effective in improving soil properties. Soil additives, such as biostimulant products, have not proven to be consistently effective through research. The management challenge is to provide an urban environment that functions like the natural environment.

Key Words. Biostimulants; Bulk Density; Cation Exchange Capacity; Mechanical Resistance; pH; Soil Oxygen; Soil pH; Soil Salt; Soil Water; Temperature.

In urban and suburban areas, the soil environment often creates numerous challenges for tree root growth. Urban soil has been defined as, "a soil material having a non-agricultural, manmade surface layer more than 50 cm thick that has been produced by mixing, filling, or by contamination of land surface in urban and suburban areas" (Bockheim 1974). Urban soils are often highly altered from the natural state, and human activity is the primary agent of the disturbance. They generally have high vertical and spatial variability, modified and compacted soil structure, an impermeable crust on the soil surface, restricted aeration and water drainage, interrupted nutrient cycling, altered soil organism activity, presence of anthropogenic materials and other contaminants, and altered temperatures (Craul 1985; Bullock and Gregory 1991; Scheyer and Hipple 2005). These physical, chemical, and biological constraints of urban soils pose limitations for the growth of tree roots. Early experience gained working with the urban soils in Washington, D.C., and other difficult urban sites, led to the projection that about 80% of urban tree problems can be attributed to a poor soil environment, leading to synergistic effects of other debilitating urban stress factors producing an overall decline in plant vigor (Patterson et al. 1980).

The resources provided by the soil environment for root growth include adequate oxygen, water, and nutrients, non-limiting penetration resistance, acceptable pH range, and robust biological activity. Presence of contaminants or pathogens can be harmful to roots. Any one of these factors can limit root growth and development, even if all others are in adequate supply.

Urban environments are quite different from the natural environment to which trees are adapted, yet they must provide the same resources for growth if trees are to maintain a healthy balance between the crown (supplier and user of energy, user of nutrients and water) and root system (supplier of water and nutrients, user of energy). The management challenge is to provide an urban environment that functions like the natural environment, though its appearance may be different.

Recent reviews have described root architecture and rhizosphere ecology in the urban environment (Day et al. 2010a; Day et al. 2010b) and serve as a foundation for this review of research summarizing our current understanding of soil management techniques for urban trees.

SOILS INFLUENCE ROOT DEVELOPMENT

Water, oxygen, mechanical resistance, temperature, soil reaction, cation exchange capacity, contaminants, and biology are soil factors that directly affect root growth. Water absorbed by plants transports nutrients and cools leaves through evaporation. Soil oxygen is essential for respiration in plant roots. Mechanical resistance physically limits root exploration of the soil (Letey 1985). Temperature controls certain metabolic processes in roots.

Water can be a dominant controlling factor, but all are interconnected. The influence of each factor on root growth will first be reviewed individually, followed by a review of their interactions. Because altering one factor does affect the quality of others, management practices to improve root growth will consider the effects on all factors together.

Water

The amount of water held in the soil is related to texture and structure. Sandy soils contain less than 10% total water at field capacity. Clay soil can contain as much as 35% water, but more is unavailable to plant roots. The difference between the water content at field capacity and the water content at the permanent wilting point is the amount of available water.

Urban soils often have less structure and greater bulk density than most undisturbed natural soils. The resulting reduction in pore space reduces plant available water (Letey 1985; Craul 1992). The loss of natural soil structure is one of the most important limitations to tree growth in urban areas (Stewart and Scullion 1989).

Measurement

Assessment of soil moisture status in the root zone is necessary to determine the need for site improvements, such as improved drainage, or supplemental irrigation. Soil moisture can be measured by a variety of methods. The hand-feel method (Ross and Hardy 1997) is simple and fast. If the soil retains its shape after compression between the fingers, but is not sticky, the moisture content is favorable. This method can be prone to error since it requires experience and can be subjective. Determining gravimetric soil water is the most accurate, simple method not requiring special equipment. Soil is weighed before and after oven drying.

The most widely used and least-expensive water-potential measuring device is the tensiometer. The tensiometer establishes a quasi-equilibrium condition with the soil water system through a porous ceramic cup. Electrical resistance blocks consist of electrodes encased in some type of porous material that reaches a quasi-equilibrium state with the soil. They are less sensitive in wet soils. Time-domain reflectometry and neutron scatter methods can be very precise, but require expensive, specialized equipment, and their use in arboriculture is primarily limited to research (World Meteorological Association 2008).

Effect on Root Growth

Fine root growth is slowed up to 90% by low soil water content (Barnett 1986; Walmsley et al. 1991; Kätterer et al. 1995; Torreano and Morris 1998; Meier and Leuschner 2008; Olesinski et al. 2011). Root growth decreases rapidly in most species when soil moisture is reduced to 10%–14% on an oven-dry basis (Newman 1966; Lyr and Hoffmann 1967) or -50 kPa soil moisture tension (Bevington and Castle 1985). This can result in a significant decrease of the root/shoot ratio (Blake et al. 1979; Meier and Leuschner 2008), especially during periods of active root growth (McMillin and Wagner 1995).

As soil begins to dry, the development of branch roots is inhibited more than the growth of primary roots (Wright et al. 1992). When roots are drought stressed, they mature rapidly toward the tip, decreasing absorption, and reducing future growth (Kaufmann 1968; Bilan 1974). As the effective absorbing surface is diminished, the roots do not regain their full capacity for water uptake until new root tips can be produced. When roots are rewatered immediately after cessation of elongation, roots may not resume elongation for at least one week. Resumption of root growth can take up to five weeks if water is withheld longer (Bilan 1974).

According to the optimal partitioning theory, plants should allocate relatively more carbon and nutrients to root growth than to aboveground growth when plant growth is limited by water shortage (Bloom et al. 1985). However, some research reports have shown a decrease in root length density when water is withheld (Ruiz-Canales et al. 2006; Abrisqueta et al. 2008). This decrease may be explained by increased fine-root turnover

—higher fine-root mortality concurrent with increased root growth (Meier and Leuschner 2008).

In wet soils, the growth of roots tends to be confined towards the soil surface. In dry soils, root growth can be shifted downward due to water depletion in surface soils (Torreano and Morris 1998). When urban soils limit rooting depth, the ability of tree root systems to respond to periods of drought and high soil moisture may be very limited.

Flooding of soil usually leads to greatly reduced root growth, and death of many of the fine absorbing roots. The small root systems of flooded trees reflect the combined effect of reduction in root initiation and reduced growth of existing roots, as well as decay of the original root system. Because root growth is usually decreased more than shoot growth by high soil moisture, drought tolerance of flooded trees is reduced after the flood waters recede. This change reflects the inability of the small root systems to supply enough water to meet the transpirational requirements of the crown (Kozlowski 1985).

Responses of tree species to flooding vary widely (White 1973; Bell and Johnson 1974; Whitlow and Harris 1979). Tolerance can vary from only a few hours to many days or weeks, depending on the species, the organs directly affected, the stage of development, and external conditions, such as temperature. Roots are often more susceptible to oxygen deficiency than shoots (Vartapetian and Jackson 1997). Broadleaved trees as a group are much more flood-tolerant than conifers. Older trees usually tolerate flooding better than seedlings or saplings. Flooding during the dormant season is much less harmful than flooding during the growing season (Heinicke 1932). The greater injury and growth reduction by flooding during the growing season are associated with high oxygen requirements of growing roots with high respiration rates (Yelenosky 1963; Koslowski 1985).

Aeration

Respiration by plant roots and other soil organisms consumes oxygen and produces carbon dioxide. In unsaturated soils, the soil air connects directly with the aboveground atmosphere, but diffusion of gasses through the soil is slowed by water and soil particles. Oxygen concentrations decline and carbon dioxide concentrations increase with depth due to the oxygen demands of the roots, the soil fauna, fungi, and microbes. Oxygen deficiency in roots will be more likely to occur in warm soils than in cooler soils when reduced respiration is more balanced with diffusion rates (Yelenosky 1963; Armstrong and Drew 2002).

For most species, approximately 10%–12% oxygen in the soil atmosphere is needed for adequate root growth (Stolzy and Letey 1964; Tackett and Pearson 1964; Stolzy 1974; Valoras et al. 1964; Gilman et al. 1987; Mukhtar et al. 1996), and growth may cease at 5% oxygen (Stolzy 1974). Soil carbon dioxide concentration can be damaging to roots when it reaches 0.6% (Gaertig et al. 2002).

For most species, root growth is reduced or stopped when the oxygen diffusion rate (ODR) drops below 0.2 $\mu g/cm^2/min$. Most plants are severely stressed between 0.2 and 0.4 µg/cm2/min. Above 0.4 $\mu g/cm^2/min$, plants grow normally (Stolzey and Letey 1964; Valoras et al. 1964; Lunt et al. 1973; Stolzy 1974; Erickson 1982; Blackwell and Wells 1983).

Redox potential can also be used as a measure of the oxygen status of the soil. Soil redox potentials of 400–700 mV are generally considered well aerated. Root growth of most species is stopped at a soil redox potential of 350 mV, though roots of more water-tolerant species (e.g., *Taxodium distichum*) are able to grow until the redox potential reaches 200 mV (Carter and Rouge 1986; Pezeshki 1991; Stepniewski et al. 1991).

Soil aeration is impacted by urban landscape features. In undisturbed, well-drained soil, oxygen and carbon dioxide contents can be near atmospheric levels close to the soil surface, decreasing most rapidly in the first 30 cm (Yelenosky 1963; Brady and Weil 1996). When not paved, vegetated and nonvegetated urban sites can be as well-aerated as forest stands (Gaertig et al. 2002). However, if topsoils are sealed or compacted, gas exchange between the soil and the atmosphere is interrupted (Gaertig et al. 2002). Oxygen content was reduced to 14.5% and carbon dioxide content was increased to 6% at 15 cm depth under an unpaved parking lot. The same levels were not reached until 90 cm depth in the adjacent undisturbed forest soil (Yelenosky 1963). In another study, there were minimal differences in soil oxygen between pavement and turf in the top 45 cm (Hodge and Boswell 1993). However, soil oxygen measurements were made only 75 cm from the edge of the pavement and oxygen could have diffused laterally from the nearby exposed soil. While it is commonly accepted that stone pavement with gaps allows for aeration of the soil, there was no difference in gas diffusivity between completely sealed surfaces (asphalt) and areas with flagstone or cobblestone with gaps in between (Weltecke and Gaertig 2012).

A water table less than 50 cm deep can reduce oxygen below levels considered sufficient to sustain vigorous root growth to within 5 cm of the soil surface (Callebaut et al. 1982). Elevated berm soils can be more aerated than surrounding soils at grade (Handel et al. 1997).

Measurement

Assessment of soil oxygen can be helpful in choosing the appropriate plant for the site, or understanding whether site modifications, such as improved drainage, may be necessary. However, measuring oxygen levels in the soil can be challenging: equipment can be expensive and suited primarily for research applications. Measurement at any moment in time may not reflect sustained conditions, and not all measurements provide the same information related to root growth.

Oxygen content, expressed as a percentage, is the amount of oxygen in the soil gases (the aboveground atmosphere contains 21% oxygen). ODR measures the rate at which oxygen can move through the soil to replace oxygen that is used by the root. ODR can be a better indicator of soil aeration (i.e., oxygen availability to roots) than oxygen content because it is possible to have a high soil oxygen concentration, but very low diffusion rate (MacDonald et al. 1993). The oxygen concentration in the soil atmosphere may not vary substantially at monitoring sites over time, or in response to changes in soil moisture. In contrast, ODR is strongly influenced by soil moisture and bulk density. Oxygen concentration was not consistently low enough to severely inhibit root function at sites where trees were declining. At the same time, ODR values within the root zones of declining trees were invariably in a range considered injurious to roots, while ODR values around vigorous trees were favorably high (Stolzy 1974; MacDonald et al. 1993).

Rusting pattern on steel rods can be used to assess soil anaerobism over an extended period (Carnell and Anderson 1986; Hodge and Knott 1993; Hodge et al. 1993) and has been related to fine-root development of trees (Watson 2006a). Fine-root density in soils, where rust was present on over 60% of the steel rods, was generally three times greater than in soils with less than 25% rusting. This method can provide an indication of soil aeration over a period of months and up to a depth of 60 cm without the use of expensive equipment.

Effect on Root Growth

Growing root tips have high oxygen requirements, and fine-root density is often reduced when oxygen availability is low (Koslowski 1985; Gaertig et al. 2002; Weltecke and Gaertig 2012). In older parts of the root, the oxygen demand can be approximately half that of the tip (Armstrong and Drew 2002). Root dysfunction as a result of inadequate oxygenation can modify plant growth and development through interference in water relations, mineral nutrition, and hormone balance (Kramer and Kozlowski 1979; Armstrong and Drew 2002).

Species vary in their root system tolerance to low soil aeration. For example, loblolly pine (*Pinus taeda*) grew better at low aeration conditions (either high compaction or high water content) than ponderosa pine (*Pinus ponderosa* var. *scopulorum*) or shortleaf pine (*Pinus echinata*) (Siegel-Issem et al. 2005). Lists of species' tolerance to flooding, which reduces soil aeration, are available (White 1973; Bell and Johnson 1974; Whitlow and Harris 1979).

In some trees, such as willow (Salix), alder (*Alnus*), poplar (*Populus*), tupelo (*Nyssa*), ash (*Fraxinus*), baldcypress (*Taxodium*), and birch (*Betula*), oxygen can move down to the roots internally through intercellular spaces. This oxygen-transporting tissue within roots is called aerenchyma. It is not uncommon in the subapical parts of wetland plant roots for as much as 60% of the root volume to be gas space for diffusion of oxygen from the shoot (Drew 1997; Armstrong and Drew 2002). Enough oxygen can be transported so that some is released into the soil immediately surrounding the roots (Hook et al. 1971; Armstrong and Read 1972).

Mechanical Resistance

Bulk density is a measure of dry mass per unit volume and used to describe limits to root growth in compacted soil. Soil strength, expressed as penetration resistance, is a broader indicator of constraints on root growth that accounts for soil moisture, as well as bulk density (Baver et al. 1972; Gerard et al. 1982; Ehlers et al. 1983; Taylor and Brar 1991).

Parent material is the deepest and densest layer in the soil profile. As soils develop, formation of structure in the overlying horizons reduces bulk density. Clay deposition in the B horizon tends to fill existing pore spaces, making it denser as clay content increases (Foth 1990). Roots compact the soil nearby as they increase in size, and they also transmit the weight of the tree and forces generated by the wind onto the soil (Greacen and Sands 1980).

In urban and suburban settings, soil formation has been interrupted by removal, grading, mixing, or other disturbances. Thus, urban soils can have high bulk densities (Yang et al. 2005; Feng et al. 2008). Urban soil mean bulk density values of 1.6 g cm^{-3} have been reported, with individual values as high as 2.63 g cm^{-3} (Patterson 1977; Short et al. 1986; Jim 1998a; Jim 1998b). These levels of compaction restrict root growth for many woody species, especially in finer-textured soils.

Compaction occurs very quickly. On fine- to medium-textured soils, half of the increase in soil bulk density and soil strength occurred in the first two passes of traffic. Coarse soils were slightly more resistant to compaction (Brais and Camire 1998). Fine-textured soils are also slower to recover than coarse-textured soils (Page-Dumroese et al. 2006).

Soil on construction sites was heavily compacted to depths of 0.3–0.8 m (Randrup 1997). In a survey of areas to be landscaped near new residential and commercial construction, mean soil bulk density was found to be 1.56 g cm^{-3}, which represents a 0.5 g cm^{-3} increase over adjacent undisturbed areas (Alberty et al. 1984). Bulk densities in fenced (undisturbed) areas ranged from 1.05 to 1.42 g cm^{-3}, while in unfenced areas, bulk densities were 1.56 to 1.90 g cm^{-3}; often exceeding the 1.60 g cm^{-3} critical bulk density for the loam soils on the study site (Lichter and Lindsey 1994). In another study, the absence of differences between protected and unprotected areas was attributed to traffic occurring on areas not meant for traffic (Randrup and Dralle 1997).

Measurement

To determine bulk density, a soil core of known volume is oven dried at 105°C and weighed. Care is exercised in the collection of cores so that the natural structure of the soil is preserved. Any change in structure is likely to alter pore space and bulk density. Excavation methods are better for a gravelly soil. A quantity of soil is excavated, dried, and weighed, along with determining the volume of the excavation by filling the hole with sand of which the volume per unit mass is known, or water in a rubber liner (Grossman and Reinsch 2002).

Penetrometers are used to measure soil strength. Type of equipment used and soil moisture content will affect measurement. Penetrometers with 30-degree tips and diameter sizes of 12.8 and 20.3 mm are standard. The smaller cone size is for use in harder (more resistant) soils (American Society of Engineers 1992; Lowery and Morrison 2002).

Soil strength increases with bulk density and decreases with soil water content (Taylor and Burnett 1964; Eavis 1972; Blouin et al. 2008.) Fine-textured soils are the most limiting (Gerard et al. 1982), but penetration resistance can be affected more by water content than by texture. Penetration resistance in a dry soil (−1500 kPa) exhibited a maximum at clay content of 35%, while in a moist soil (−10 kPa) penetration resistance was minimally affected by texture (Vaz et al. 2011).

Effect on Root Growth

The bulk density that limits root growth varies with soil texture (as reviewed in Daddow and Warrington 1983) and soil moisture (Day et al. 2000). Greater development of structure in fine-textured soils accounts for their lower bulk density as compared to coarse-textured soils. A bulk density of 1.60 g cm^{-3} would be limiting in a clay loam, but not in a sandy loam (Foth 1990). Summary tables (Jones 1983; Daddow and Warrington 1983; NRCS Soil Quality Institute 2000 (Table 1) are consistent with reports of root restriction in individual tree species (Minore et al. 1969; Chiapperini and Donnelly 1978; Webster 1978; Zisa et al. 1980; Heilman 1981; Tworoski et al. 1983; Alberty et al. 1984; Pan and Bassuk 1985; Simmons and Pope 1985; Reisinger et al. 1988; Watson and Kelsey 2006).

Reconstruction of soil profiles from six forest sites in greenhouse tests showed root and shoot growth in soil from lower horizons (10–30 cm) averaged only 41% of that in topsoil, a significantly greater restriction of growth than that achieved through

Table 1. General relationship of soil bulk density to root growth based on soil texture (adapted from NRCS Soil Quality Institute 2000).

Soil texture	Ideal bulk densities ($g\ cm^{-3}$)	Bulk densities that may affect root growth ($g\ cm^{-3}$)	Bulk densities that restrict root growth ($g\ cm^{-3}$)
Sands, loamy sands	<1.60	1.69	>1.80
Sandy loams, loams	<1.40	1.63	>1.80
Sandy clay loams, clay loams	<1.40	1.60	>1.75
Silts, silt loams	<1.30	1.60	>1.75
Silt loams, silty clay loams	<1.10	1.55	>1.65
Sandy clays, silty clays, some clay loams (35%–45% clay)	<1.10	1.49	>1.58
Clays (>45% clay)	<1.10	1.39	>1.47

compaction of up to 0.17 g cm^{-3} greater than the undisturbed field sites (25%). Topsoil displacement and profile disturbance may be more damaging than soil compaction (Williamson and Neilsen 2003).

Soil strength, not bulk density, was found to be the critical impedance factor controlling root penetration (Taylor and Burnett 1964; Zisa 1980). Reduced survival and growth of sugar maple (*Acer saccharum* 'Seneca Chief') and callery pear (*Pyrus calleryana* 'Redspire') in compacted soil were due to mechanical impedance, rather than limited aeration and drainage (Day et al. 1995). The critical limit of soil strength above which woody plant roots will likely be greatly restricted is 2.5 MPa when measured with a standard penetrometer (Taylor et al. 1966; Greacen and Sands 1980; Zisa et al. 1980; Ball and O'Sullivan 1982; Abercrombie 1990; Day and Bassuk 1994; Blouin et al. 2008).

Root growth decreases as compaction and soil strength increase (Youngberg 1959; Taylor et al. 1966; Sands et al. 1979; Bengough and Mullins 1990; Jordan et al. 2003; Blouin et al. 2008). Both controlled studies (Minore et al. 1969) and field observations (Forristall and Gessel 1955) have shown that the capacity for root growth in compacted soil often varies among plant species. For example, root growth of Siberian larch (*Larix sibirica*), English oak (*Quercus robur*), western red cedar (*Thuja plicata*), and Formosa acacia (*Acacia confusa*) were little affected by soil bulk density as high as 1.89 g cm^{-3}, while Norway spruce (*Picea abies*), Douglas fir (*Pseudotsuga menziezii*), littleleaf linden (*Tilia cordata*), and tallow lowrel (*Litsea glutinosa*) were the least capable of growing roots in compacted soil (Forristall and Gessel 1955; Korotaev 1992; Liang et al. 1999). As little as 0.14 g cm^{-3} can make a difference (Minore et al. 1969).

Soil compaction can affect root distribution. Root penetration depth can be restricted by soil bulk density (Halverson and Zisa 1982; Nambiar and Sands 1992; Laing et al. 1999). If not all parts of a root system are equally exposed to compaction, compensatory growth by unimpeded parts of the root system may compensate, and the distribution but not the total length of roots may be altered (Unger and Kaspar 1994).

Individual root tips can penetrate only those soil pores that have a diameter greater than that of the root. Roots often grow into root channels from previous plants, worm channels, structural cracks, and cleavage planes, thereby tapping a larger reservoir of water and mineral nutrients. In very compacted soils, root growth may be confined almost entirely to these pores and cracks (Taylor et al. 1966; Eis 1974; Patterson 1976; Gerard et al. 1982; Ehlers et al. 1983; Hullugalle and Lal 1986; Wang et al. 1986; Bennie 1991; van Noordwijk et al. 1991). If not present, roots may undergo redirection of growth from deeper layers toward uncompacted surface soil when downward growth is restricted by high bulk density (Waddington and Baker 1965; Heilman 1981; Gilman et al. 1987). The net result is the proliferation, if not concentration, of roots at a shallow depth (Gilman et al. 1982; Weaver and Stipes 1988; Jim 1993a). Such a shallow root system will be more affected when surface soils dry during periods of drought.

There is a tendency to form more lateral roots with increasing soil strength (Gilman et al. 1987; Misra and Gibbons 1996). Length of primary and lateral roots of shining gum (*Eucalyptus nitens*) was reduced 71% and 31%, respectively, with an increase in penetrometer resistance from 0.4 to 4.2 MPa. High mechanical resistance will also tend to increase the root diameter behind the root tip (Taylor et al. 1966; Eavis 1972; Russell 1977; Bengough and Mullins 1990; Misra and Gigbons 1996), and the growth and shape of root cells are altered (Pearson 1965). Differences among species in their ability to penetrate strong soil layers appear to be due to differences in root diameter (Clark et al. 2003).

Temperature

Urban soils can be warmer due to surrounding pavements and lack of vegetation cover. Unvegetated playground soils in Central Park (New York City, New York, U.S.) were 3.13°C warmer than an adjacent wooded area (Mount et al. 1999). Maximum summer soil temperatures under pavement in the northern United States were 32°C–34°C, and up to 10°C warmer than nearby unpaved areas (Halverson and Heisler 1981; Graves and Dana 1987). In Texas, U.S., summer soil temperatures under pavement exceeded 48°C, 10°C warmer than unpaved areas, and remained above 35°C for all but a short time at night. Temperatures are highest under dark pavements (Arnold and McDonald 2009).

Effect on Root Growth

Biological activity in the soil, and therefore root growth, varies with temperature (Lloyd and Taylor 1994). Root growth occurs over a wide range of temperatures, but is much slower at low and high temperatures. Reported minimum temperatures for root growth range from 2°C to 11°C (Lyr and Hoffmann 1967; Solfjeld and Pedersen 2006). Sugar maple (*Acer saccharum*) roots began to grow in spring as soils warmed to 5°C, but initial root growth may be quite slow at such low temperatures. Active root growth has been reported to begin when soil temperatures reach 10°C–15°C (Nambiar et al. 1979; Carlson 1986; Harris et al. 1995; Solfjeld and Pedersen 2006). Optimum temperatures for root growth have been reported at 18°C–32°C (Lyr and Hoffman 1967; Larson 1970; Nambiar et al. 1979; Struve and Moser 1985; Headley and Bassuk 1991; Harris et al. 1995; Solfjeld and Pedersen 2006; Richardson-Calfee et al. 2007).

The high temperature at which root injury begins to occur is around 34°C (Graves and Wilkins 1991; Graves 1994; Graves 1998; Wright et al. 2007). Roots of most woody species are killed at 40°C–50°C (Wong et al. 1971). Maximum temperatures for active growth have been reported at 25°C–38°C, depending on the species (Proebsting 1943; Wong et al. 1971; Gur et al. 1972; Graves et al. 1989a; Graves et al. 1989b; Graves 1991; Martin and Ingram 1991; Graves and Aiello 1997; Arnold and McDonald 2009). Direct heat injury of roots can occur when the soil remains above 32°C for extended periods of time (Graves 1998), and the longer the duration of high temperatures, the more root growth is reduced (Graves et al. 1989b; Graves and Wilkins 1991). Honeylocust (*Gleditsia triacanthos*) is the only temperate tree species reported to sustain growth at root-zone temperatures above 32°C (Graves et al. 1991).

The root tissues of most woody plants can be killed at soil temperatures of -5°C to -20°C (Havis 1976; Studer et al. 1978; Santamour 1979; Pellett 1981; Lindstrom 1986; Bigras and Dumais 2005), although roots of black spruce (*Picea mariana*) were not affected by temperatures as low as -30°C (Bigras and Margolis 1996). Young roots are less freeze-tolerant than mature roots (Bigras and Dumais 2005).

Soil pH

Plant performance is strongly affected by nutrient availability, which in turn is influenced by soil pH (acidity or alkalinity). Most nutrients are available at optimal levels in slightly acid to neutral soils (pH between 5.5 and 7.2), and trees generally grow best in this pH range. Soil pH can be measured with electronic meters or colorimetric tests based on color of solutions or strips.

Urban soils tend to have higher soil pH than their natural counterparts. In Berlin, Germany, a pH of 8 was observed streetside, compared to a pH of less than 4 within a forest a short distance from the street (Chinnow 1975). Over half of soils sampled in Hong Kong, China, were rated strongly (pH 8.5–9) to very strongly (pH 9–9.5) alkaline, while surrounding soils were acidic at pH 4–5 (Jim 1998b). Streetside soils of Syracuse, New York, U.S., had a pH range of 6.6 to 9.0 with an average of about 8.0 (Craul and Klein 1980). Urban soils of Philadelphia, Pennsylvania, U.S., ranged from 3.7 to 9.0 with a mean of 7.6 (Bockheim 1974).

Elevated pH values have been attributed to the application of calcium or sodium chloride as road and sidewalk deicing compounds in northern latitudes, irrigation with calcium-enriched water (Bockheim 1974), and the surface weathering of concrete and limestone buildings and sidewalks (Bockheim 1974; Messenger 1986; Okamoto and Maenaka 2006).

Effect on Root Growth

The effects of pH on root growth are primarily related to nutrient availability. Some nutrients, such as iron and manganese, become less available in alkaline soils (pH above 7.2) because of chemical changes caused by the alkalinity. Other nutrients, such as phosphorous, become less available in highly acid soils (pH less than 5.5). When the pH is 4.5 or less, aluminum toxicity can restrict root growth (Foth 1990; Jim 1993b). In most plant systems, aluminum toxicity has a direct effect on root growth by inhibiting cell division in the root apical meristem (Kochian 1995).

A nutrient deficiency caused by sub-optimum soil pH could actually stimulate root growth in order to explore larger volumes of soil to acquire additional nutrients and alleviate deficiency symptoms (Ingestad and Lund 1979; Ericssson and Ingestad 1988).

Cation Exchange Capacity

Cation exchange capacity (CEC) is a measure of the nutrient-holding (adsorption) power of the soil. Once adsorbed, cationic minerals are not easily lost when the soil is leached by water and therefore provide a nutrient reserve for plant roots. CEC is highly dependent upon soil texture and organic matter content. In general, the more clay and organic matter in the soil, the higher the CEC. Small clay soil particles have a large, negatively charged surface area for their size and hold relatively large amounts of ions. Organic matter particles have even more negative surface charges on the surface than clay for nutrient exchange. Sandy soils have low CEC due to their low organic matter and clay content.

CEC is usually greatest at the surface where organic matter accumulates. Increasing clay with depth can act to counterbalance the decrease in organic matter and reduction of CEC. The CEC of most soils increases with pH (Craul 1992; Brady and Weil 1996).

CEC is determined by laboratory testing, and methods vary with the soil type. Reported urban soil CEC values have been 5–12 cmol/kg (Short et al. 1986; Jim 1998b). Normal values vary, from 5 cmol/kg to 25 cmol/kg, depending on texture, organic matter content, and pH (Foth 1990; Landon 1991; Brady and Weil 1996).

Contaminants

Salt in soil inhibits plant water uptake by lowering the osmotic pressure of soil water (Prior and Berthouex 1967). This reduces the water uptake of trees and symptoms of decline mimic those of drought (Herrick 1988). Once salt enters the roots, it upsets the osmotic balance within root cells (Janz and Polle 2012) and is toxic to the endomycorrhizae (Guttay 1976). The increased sodium on the cation exchange sites also breaks down soil structure (Holmes 1961; Hutchinson and Olson 1967), decreasing the permeability and water-holding capacity of the soil. All of these factors may contribute to a decline in tree health.

Damage from salt-contaminated soil occurs frequently in urban areas where large amounts of salt are used for deicing roads and pavements. Sodium chloride is the most common deicer applied. Parkways, street tree planter boxes, highway medians, and roadsides are locations where soil accumulation of deicing salts is highest. Sodium levels were 5.4 times higher and chloride was 15 times higher in the center of newly installed, narrow, raised medians along an urban highway after one winter, compared to the center of wide medians along the same roadway. The high levels were attributed to proximity to high speed traffic and its associated spray and splash (Hootman et al. 1994). Elevated levels of sodium have been reported in the soil up to 30 m from the highway and elevated levels of soil chlorine to a distance of 61 m (Langille 1976; Hofstra et al. 1979; Simini and Leone 1986). In contrast, rural highway studies show salt levels decline rapidly with distance to pavement (Herrick 1988; Cunningham et al. 2008). The release of salts from rapid-release forms of fertilizer can also elevate soil salt levels (Jacobs et al. 2004).

Reclaimed wastewater (RWW) and groundwater used to irrigate urban plantings in arid climates can be highly saline. Sodium and chloride are the major chemical constituents in RWW that are potentially detrimental to plants (State of California 1978; Schaan et al. 2003). Compared with sites irrigated with surface water, sites irrigated with RWW exhibited up to 187% higher electrical conductivity (EC) and 481% higher sodium adsorption ratio (SAR) (Qian and Mecham 2005; Schuch et al. 2012). Soil types play a role on soil salinization as much as water quality. The highest salinity was found in clay and the lowest in sand (Miyamoto 2012).

The best method for assessing soil salinity is to measure the electrical conductivity of soil solution extracts. Conductivity of 2 dS/m (deci-Siemens/meter) is considered harmful to salt-sensitive plants (Foth 1990; Jacobs and Timmer 2005). All but very salt-tolerant plants will be affected at 4 dS/m. Czerniawska-Kusza et al. (2004) found necrosis and chlorosis in leaves at levels of 132 µg Na^+/g of soil. Soil chloride ion concentrations of up to 200 µg/g are not considered harmful to plants (Jim 1998a).

Deicing salt can cause the death of surface roots in roadside trees (Wester and Hohen 1968; Krapfenbauer et al. 1974; Guttay 1976; Jacobs et al. 2004; Madji and Persson 1989), though the risk of root damage associated with salt concentrations levels appears to be dependent on species, age of root system, and soil moisture availability (Jacobs and Timmer 2005). Damage may result from osmotic and/or specific ion effects (Dirr 1975). Root rot caused by *Phytophthora* sp. can increase with soil salinity as well (Blaker and MacDonald 1985; Blaker and MacDonald 1986). Indirect damage occurs when sodium displaces other ions from soil cation exchange sites reducing their availability, and breaks down soil structure leading to soil compaction (Herrick 1988; Dobson 1991; Hootman et al. 1994).

Trees growing in soils with high salt levels tended to have more twig dieback and less twig growth than those growing in soils with lower salt levels (Berrang et al. 1985). Sodium chloride and other salts accumulating in the root zone may instigate and exacerbate street tree decline (Hootman et al. 1994).

Heavy metals is a term generally used to describe a group of metallic elements that can be toxic to plants and animals. Some, such as copper, molybdenum, and zinc are essential trace elements, but excessive levels can be toxic (Prasad 2004). Heavy metal contamination tends to be greater toward the city center and in areas of commercial and industrial land use (Carey et al. 1980; Blume 1989; Wang and Zhang 2004). City center and wasteland soils generally had enhanced heavy metal concentrations to at least 30 cm depth (Linde et al. 2001). Soils on the National Mall in Washington, D.C., U.S., had elevated levels of lead, zinc, nickel, copper, and cadmium (Short et al. 1986). Concentrations of heavy metals in roadside soils decrease with distance from traffic and depth in the soil profile. The contamination has been related to the composition of gasoline, motor oil, and car tires, and to roadside deposition of the residues of these materials (Lagerwerf and Specht 1970; Madji and Persson 1989). Long-term sewage sludge application may result in the accumulation of Zn, Cu, and Ni in the soil and plant (Bozkurt et al. 2010).

Soil heavy-metal data has been published for several cities (Lagerwerf and Specht 1970; Carey 1980; Blume 1989; Jim 1998a). Levels of many elements were higher on urban sites than suburban and rural sites up to 10 times or more. No plant damage was reported with these higher levels.

Soil Biology

Soil organisms are an important component of a healthy soil that promotes root growth. The ratio of fungal to bacterial biomass is often near 1:1 in grass and agricultural soil ecosystems. With reduced disturbance, fungi become more plentiful, and the ratio of fungi to bacteria increases over time. Forests tend to have fungal-dominated microflora. The ratio of fungal to bacterial biomass may be 5:1 to 10:1 in deciduous forests and 100:1 to 1000:1 in coniferous forests (Soil and Water Conservation Society 2000). Assessing abundance of soil bacteria and fungi and mycorrhizal colonization of roots requires extensive skill and laboratory equipment.

The zone of soil adjacent to plant roots with a high population of microorganisms is the rhizosphere. Bacteria feed on sloughed-off plant cells and the proteins and sugars released by roots. The protozoa and nematodes that "graze" on bacteria are also concentrated near roots. Thus, much of the nutrient cycling and disease suppression needed by plants occurs immediately adjacent to roots (Soil and Water Conservation Society 2000). Rhizosphere pH can be up to two units different than the rest of the soil (Marschner and Römbeld 1996).

Mycorrhizae are symbiotic relationships that form between common soil fungi and plants. The benefits of mycorrhizal associations of tree roots are well established (Smith and Read 1997). The fungi colonize the root system of a host plant, providing increased nutrient absorption capabilities, while the plant provides the fungus with carbohydrates from photosynthesis. Mycorrhizae offer the host plant increased protection against certain pathogens.

Urban planting sites are often considered to be of poor soil quality, but mycorrhizal inoculum (spores) was more abundant in urban soil than in forest soil in one study (Wiseman and Wells 2005). Some mycorrhizal fungi colonizing littleleaf linden (*Tilia cordata*) roots were common to both street trees and forest trees. Others were not. Colonization levels were high on both street and forest trees (Nielsen and Rasmussen 1999; Timonen and Kauppinen 2008). Native desert trees had greater colonization by arbuscular mycorrhizal fungi (AMF) than residential landscape trees, and AMF species composition differed at the two site types (Stabler et al. 2001).

Interdependence of Soil Factors

As a result of the interdependence of soil properties, the status of one soil factor can have an effect on all others; an understanding of their interrelationships is important for proper management.

Water and Air

Increasing soil moisture reduces soil aeration when water replaces the air normally held in the pores of the soil. Water slows the diffusion of oxygen to 1/10,000 of that in air, and it reduces its concentration to about 1/32 of that in air. The net result is an effective resistance to flow that is around 320,000 times greater in saturated soil than that of air (Armstrong and Drew 2002).

Water and Compaction

Compaction can decrease the number of days of available water in clay-loam soil. However, compaction can increase the number of days that water is available in a sandy loam soil (Gomez et al. 2002).

Tree roots can grow successfully in significantly compacted soils provided soil moisture is readily available (Zisa et al. 1980; Pittenger and Stamen 1990; Bulmer and Simpson 2005; Siegel-Issem et al. 2005). Resistance to penetration in a clay loam soil was found to decrease from 3.5 MPa (limiting) to 2.1 MPa (non-limiting) when volumetric soil moisture increased from approximately 27% to 40% (Day et al. 1995). Roots of spotted gum (*Corymbia maculata*) and red-flowering gum (*C. ficifolia*) were able to penetrate soil compacted to a bulk density of 1.6 g cm^{-3} at 7% soil moisture, but when moisture was increased to 10% roots could penetrate soils of 1.8 g cm^{-3} (Smith et al. 2001).

Species can vary in their ability to capitalize on reduced penetration resistance of wet soils. Silver maple (*Acer saccharinum*) roots can grow in moderately compacted soil when high soil water content decreases soil strength, even though aeration is low, whereas dogwood (*Cornus florida*) roots are unable to grow under the same low aeration conditions (Day et al. 2000).

Air and Compaction

One of the main effects of high bulk density is a restricted oxygen supply (Yelenosky 1963; Yelenosky 1964; Rickman et al. 1966). Oxygen is less restricted when the soil is dry and less pore space is filled with water (Day 1995). Oxygen diffusion rate was lowest in soils with high bulk density (MacDonald et al. 1993). Compaction from a bulk density of 1.04 g cm^{-3} to 1.54 g cm^{-3} reduced gas diffusion by 38% when soil was dry. In wet soil, however, compaction reduced diffusion by 82% (Currie 1984).

Plant response to oxygen level has been shown to interact with mechanical impedance (Gill and Miller 1956). In general, soil compaction can have a strong inhibitory effect on root penetration when the oxygen level is high, but no significant effect at a low oxygen level because root growth is already reduced by lack of aeration (Tackett and Pearson 1964; Hopkins and Patrick 1969; da Silva and Kay 1997).

Anaerobic conditions are likely to limit root growth in compacted fine-textured and poorly drained soils, whereas mechanical impedance is more likely to limit root growth in compacted coarse-textured and well-drained soils (Webster 1978).

Soil Conditions and Root Disease

Poorly aerated and poorly drained soil can increase incidence of soil-borne diseases. Root diseases are favored when soils are water-saturated (Hansen et al. 1979). Saturated soil and low oxygen supply causes a reduction in root initiation, growth of existing roots, and an increase in decay of roots, largely as a result of invasion of *Phytophthora* sp. Fungi, which tolerate low soil aeration (Stolzy et al. 1965; Sena Gomes and Kozlowski 1980; Blaker and McDonald 1981; Benson et al. 1982; Stolzy and Sojka 1984; Benson 1986; Duniway and Gordon 1986; Gray and Pope 1986; Ownley and Benson 1991). *Armillaria* root disease, also known as shoestring root rot, causes most damage on trees that are stressed by one or more abiotic or biotic factors. These may include drought, soil compaction, and other soil problems common on urban sites (Worall 2004).

Root Development and Nutrient Uptake

When soil factors limit root development there can be a direct impact on nutrient uptake. Nutrient deficiencies can occur when there is insufficient uptake by the roots and use by the crown. If improved soil conditions allow the root system to expand and explore a larger soil volume and supply of nutrients, the tree may overcome the deficiency and symptoms may dissipate (Ingestad and Lund 1979; Ericssson and Ingestad 1988).

MANAGEMENT PRACTICES TO IMPROVE THE SOIL ENVIRONMENT

The effectiveness of management practices to enhance soil as a medium for root growth can affect all soil factors and is influenced by soil physical properties. Soils classified as having poor physical conditions are those that require very careful management to maintain conditions favorable for root growth. Soils with good physical conditions require less careful management (Letey 1985).

Prevention

Prevention of soil compaction is preferred. Treatments to alleviate compaction can be expensive, difficult to apply, sometimes ineffective, and may injure roots (Howard et al. 1981). When only acted upon by natural forces, return to the initial, uncompacted state is slow (Hatchell et al. 1970; Froehlich and McNabb 1984; Froehlich et al. 1986; Corns and Maynard 1998; Stone and Elioff 1998; Blouin et al. 2005). Fine-textured soils are slower to recover than coarse-textured soils. Surface soils will recover most rapidly (Page-Dumroese et al. 2006). When compaction severely reduced soil aeration and root growth after a logging operation, after 14 years, recovery was limited to the top 4 cm of soil. After 18 years, recovery reached a depth of 18 cm. Only after 24 years was recovery detected throughout the rooting zone (von Wilpert and Schaffer 2006). Factors, such as a fluctuating water table, freeze–thaw cycles (Fleming et al. 1999; Stone and Kabzems 2002), and vegetation regrowth (Page Dumroese et al. 2006), may accelerate a bulk density decrease.

Mulch or gravel over geotextile can prevent soil compaction during construction. In contrast, plywood did not protect the underlying soil from compaction (Donnelly and Shane 1986; Lichter and Lindsey 1994). Fencing can be an effective way to prevent soil compaction on a construction site (Lichter and Lindsey 1994), but must be monitored and maintained to be effective (Randrup and Dralle 1997).

Amendments

The use of organic amendments, such as biosolids, animal manure, or compost, generally reduces the bulk density of compacted soils (Cogger 2005; Garcia-Orene et al. 2005), although this is not always the case (Patterson 1977). The proposed mechanisms for this phenomenon are that the high density substrate is simply being diluted with a low-density material (the amendment) or that the amendment physically increases porosity (Clapp et al. 1986; Cogger 2005). Organic amendments can increase root growth (Beeson and Keller 2001; Davis et al. 2006), microbial activity (van Schoor et al. 2008) and CEC. Composted organic matter is most effective, as the humus component has the greatest CEC. Incorporation of certain types of biochar can increase CEC (Chan et al. 2007; Laird et al. 2010), but research on this topic is still limited.

Inorganic soil amendments have been used to improve soil properties and resist compaction. Sintered fly-ash and expanded slate amendments resulted in lower bulk densities and increased pore space after being incorporated into the soil (Patterson 1977). Amendment with mixtures of gravel, expanded clay, and lava rock improved the soil aeration and soil moisture in clay loam and silty loam soils (Braun and Fluckiger 1998). These studies did not assess the effect of soil changes on root systems performance.

Hydrophilic polymer gels (hydrogels) are sometimes added to the soil to increase available water. Research has not shown that the use of hydrogels can consistently increase root growth of trees (Hummel and Johnson 1985; Keever et al. 1989; Tripepi et al. 1991; Walmsley et al. 1991; Winkelmann and Kendle 1996; Huttermann et al. 1999; Gilman 2004; Abbey and Rathier 2005).

Cultivation

Cultivation has been used with mixed results to improve soil properties and promote tree root development. Deep cultivation by ripping prior to planting decreased bulk density and soil penetration resistance (Rolf 1991; Rolf 1993; Moffat and Boswell 1997; Lincoln et al. 2007) and increased both the maximum root depth and total number of roots compared with the untreated control for Italian alder (*Alnus cordata*), Japanese larch (*Larix kaempferi*), Austrian pine (*Pinus nigra*), and European white birch (*Betula pendula*) (Sinnett et al. 2008). In other cases, ripping had no effect on rooting depth (Nieuwenhuis et al. 2003) or was reported to be effective for less than a year (Moffat and Boswell 1997).

There was no reduction in soil strength from surface soil cultivation with an air excavation tool after one year on three of four sites. Compost incorporation with air cultivation did result in a reduction of soil strength that persisted for at least three years (Fite et al. 2011).

Cultural techniques that improve soil tilth, aeration, and drainage reduce conditions favorable to root disease (Juzwik et al. 1997), and also improve host resistance by reducing or avoiding stress associated with anaerobic conditions (Sutherland 1984).

Mulch

The benefits of organic mulch are well established (Chalker-Scott 2007) and continue to be reinforced. A review of published mulch research studies showed surface mulch improved soil physical properties and tree physiology, but there was no improvement in chemical or biological properties (Scharenbroch 2009). Improvement of soil properties will enhance root growth.

Over time, organic mulches can reduce soil bulk density (Donnelly and Shane 1986; Cogger et al. 2008) and increase organic matter content (Watson et al. 1996; Johansson et al. 2006; Fite et al. 2011). Mulch can increase water infiltration (Donnelly and Shane 1986; Cogger et al. 2008), reduce evaporation from the soil surface, and increase moisture availability (Litzow and Pellett 1983; Iles and Dosmann 1999; Arnold et al. 2005; Cogger et al. 2008; Singer and Martin 2008; Fite et al. 2011). Mulch allowed a 50% reduction in irrigation while still maintaining acceptable growth and appearance (Montague et al. 2007). Mulch also insulates soil from temperature extremes (Montague et al. 1998; Iles and Dosmann 1999; Singer and Martin 2008). In December, soil under mulch was 6°C warmer than exposed sod or bare soil (Shirazi and Vogel 2007). In temperate climates, the soil may warm more slowly if new mulch is applied before the soil warms in spring (Myers and Harrison 1988).

Organic surface mulch generally improves shoot and root growth (Kraus 1998; Ferrini et al. 2008; Arnold and McDonald 2009; Scharenbroch 2009). Adding wood chip mulch to the surface of red maple (*Acer rubrum*) and sugar maple (*A. saccharum*) grown in sandy loam and clay loam, respectively, increased growth above- and belowground (Fraedrich and Ham 1982). Mulching with wood chips can result in a 30%–300% increase in fine-root development in the top 15 cm of soil (Fraedrich and Ham 1982; Green and Watson 1989; Himelick and Watson 1990). Mulches may not be beneficial for some desert plants (Singer and Martin 2009).

When a mulch layer is maintained for several years, a partially decomposed organic layer develops that holds moisture and minimizes evaporation from the soil beneath. A dense mat of roots can form in the layer of mulch as well as in the soil beneath it (Bechenbach and Gourley 1932; Watson 1988). The roots in the mulch will not be at any greater risk of desiccation, since the well-established mulch layer can hold more water than the soil itself, without decreasing aeration to the soil beneath it (Watson 1988; Himelick and Watson 1990).

Mulch reduces root competition for soil moisture and nutrients from lawn grasses (Richardson 1953; Gilman 1989; Kraus 1998). In addition to competition for water and nutrients, some lawn grasses may be able to reduce the growth of the trees through production of allelopathic chemicals. Root growth of forsythia (*Forsythia intermedia*) was suppressed by ryegrass and red fescue leachates (Fales and Wakefield 1981). Fescues have also been shown to stunt the growth of southern magnolia (*Magnolia grandiflora*) (Harris et al.1977), river redgum (*Eucalyptus camaldulensis*) (Meskimen 1970), black walnut (*Juglans nigra*) (Todhunter and Beineke 1979), and sweetgum (*Liquidambar styraciflua*) (Walters and Gilmore 1976), but specific effects on root systems were not reported.

While mulching has many benefits for soil quality and root health, there are some potential drawbacks. One concern about mulching is that it creates conditions ideal for certain disease-causing fungi. Fraedrich and Ham (1982) did not find any enhancement of the soil-borne pathogenic fungi, *Pythium* spp. and *Fusarium* spp. during their one-year study. Austrian pine saplings that were mulched with fresh needles and shoot tips from *Sphaeropsis* tip blight diseased trees developed more than twice the percentage of blighted tips. There was no *Botryosphaeria* canker or *Armillaria* root rot disease development when redbud (*Cercis canadensis*) and red oak (*Quercus rubra*) saplings, respectively, were mulched with wood chips from diseased trees (Jacobs 2005). A decrease in growth the first year after mulching, and an increase in the second year has been attributed to nitrogen immobilization in the first year followed by release the next (Hensley et al. 1988; Truax and Gagnon 1993; Erhart and Hartl 2003).

A layer of mulch can intercept rain water before it reaches the roots if the amount of water is small or the mulch is thick (Gilman and Grabosky 2004; Arnold et al. 2005; Johansson et al. 2006). Although 25 cm or more of coarse textured organic mulch does not adversely affect soil oxygen or fine root development (Watson and Kupkowski 1991; Greenly and Rakow 1995), as little as 5 cm of fine-textured organic mulch, or compost, can reduce soil oxygen to less than 10% under wet conditions, which can affect root function (Hanslin et al. 2005).

Aeration

Compressed air soil injection treatments have generally been ineffective in relieving compaction or increasing soil aeration (Yelenosky 1964; Smiley et al. 1990; Hodge 1991; MacDonald et al. 1993; Rolf 1993). Soil texture may have a strong influence on the results. Reports of success in reducing bulk density or increasing porosity were in loamy soils (Rolf 1993; Lemaire et al. 1999).

A traditional approach to aeration of compacted soil around trees is vertical mulching (i.e., drilling a pattern of holes in the root zone soil). Research on vertical mulching has provided mixed results. Holes 5 cm diameter, 45 cm deep, with or without sand-bark mix backfill, provided no benefit to Chinese wingnut trees (*Pterocarya stenoptera*) (Pittenger and Stamen 1990). Similar results were seen in sugar maple (*Acer saccharum*) when the holes were filled with perlite backfill (Kalisz et al. 1994). However, roots of Monterey pine (*Pinus radiata*) were able to utilize 10 mm diameter vertical perforations to grow the same depth as uncompacted controls, while root growth of trees on compacted soil without perforations was suppressed (Nambiar and Sands 1992; Sheriff and Nambiar 1995). Largeleaf linden (*Tilia platyphyllos*) and planetree (*Platanus* × *Acerifolia*) roots colonized the majority of the depth of 10 cm diameter, 60 cm deep holes filled with a mix of coarse sand, composted organic materials, and fertilizer, and grew deeper than in adjacent site soils (Watson et al. 1996).

Root growth in larger trenches filled with compost-amended soil was increased relative to undisturbed soil, but root growth was not increased in the soils adjacent to the trenches after 2, 4, and 14 years. Soil aeration was not measured and may not have been limiting in the undisturbed and not compacted soil adjacent to the trenches (Watson et al. 1996; Watson 2002).

pH Adjustment

Neutral to slightly acid pH is optimum for most plants. Applications of lime are used to raise soil pH. Aluminum sulfate and sulfur can help to lower pH, although high rates of aluminum sulfate may cause injury to some plants, particularly in broadleaf evergreens. The injury is believed to be caused by excessive aluminum. Ammonium sulfate may be as effective as aluminum sulfate, but neither is as effective as granular sulfur (Messenger 1984). Ammonium sulfate is sometimes used if nitrogen application is needed along with pH reduction, but applying enough to lower the pH would likely apply a quick release form of nitrogen in excess of best management practices (Smiley et al. 2007).

Enhancing root development may improve uptake of available nutrients. Improving soil quality using methods such as cultivation, addition of organic amendments, and mulching can enhance root systems (see above). Basal drench application of paclobutrazol, a tree growth regulator, increased fine-root development and relieved interveinal chlorosis commonly attributed to iron deficiency of pin oak (*Quercus palustris*) on alkaline soils (Watson and Himelick 2004).

Salt Mitigation

Soil salt accumulation can be reduced through design and engineering. Deicing salt accumulation in road median planters can be prevented by using wider planters with higher walls set farther from high-speed roads. The raised planters did not receive salt-laden runoff, splash, plowed snow, or direct application from salt spreaders (Rich and Walton 1979; Hootman et al. 1994).

Leaching of sodium from deicing salt application to roadways can be rapid in well-drained soils with adequate natural precipitation (Prior and Berthouex 1967; Cunningham et al. 2008). High soil salts and wet soils tended to occur together since poor drainage restricts the normal leaching of soil salts (Berrang et al. 1985). In arid regions, natural precipitation will not usually leach salt from the soil (Schuch et al 2008). Under low moisture conditions, moisture moves to the surface and evaporates and salt moves upward also to accumulate near the surface (Prior and Berthouex 1967). Flushing soil with water to remove salt and adding gypsum ($CaSO_4$) and fertilizers appear to be the best treatments for salt contaminated urban soils (Dobson 1991).

Selection of resistant species and cultivars can also minimize damage from salt in soils. The majority of published studies evaluate only shoot sensitivity, but growth of root systems of crapemyrtle (*Lagerstroemia*) cultivars varied in sensitivity to soil salt (Cabrera 2009).

Biostimulants

Application of commercial products to enhance root growth has been increasing. Soil application of mycorrhizal fungi have proven beneficial to trees in soils lacking the appropriate fungi, such as on strip-mining reclamation sites and in sterilized nursery beds (Smith and Read 1997). Native mycorrhizal fungi levels can be low in arid regions (Dag et al. 2009). However, growth rate of urban trees has generally been unaffected when treated with commercial inoculants at planting (Morrison et al. 1993; Martin and Stutz 1994; Roldan and Albaladejo 1994; Querejeta et al. 1998; Gilman 2001; Ferrini and Nicese 2002; Appleton et al. 2003; Abbey and Rathier 2005; Corkidi et al. 2005; Broschat and Elliot 2009; Wiseman and Wells 2009).

Vigor of the natural mycorrhizal inoculum, as well as suitability of the introduced inoculum to the ecological conditions of the site, are important factors in the success or failure of the introduced inoculum (LeTacon et al. 1992). Endemic fungi species may replace the inoculated species over time (Garbaye and Churin 1996). Mycorrhizae can develop without introduced inoculation in a favorable soil environment if natural inoculum is present (Wiseman and Wells 2009).

The quality of the inoculum may be a factor in success of inoculations. Mycorrhizal colonization of roots rarely exceeded 5% after treatment with commercial inoculants, but was up to 74% when treated with a fresh, lab-cultured inoculant (Wiseman et al. 2009; Fini et al. 2011).

Paclobutrazol (PBZ), a growth regulator used primarily to reduce shoot growth of trees, can also increase root growth under certain circumstances. Mycorrhizal colonization of root tips was unaffected by PBZ treatment, showing that mycorrhizae are not reduced by the fungicidal properties of PBZ (Watson 2006b).

Application of organic products, such as humates and plant extracts, have shown limited benefit to root growth of trees. Dose and species responses vary widely (Laiche 1991; Kelting et al. 1997; Kelting et al. 1998a; Kelting et al. 1998b; Ferrini and Nicese 2002; Fraser and Percival 2003; Gilman 2004; Sammons and Struve 2004; Abbey and Rathier 2005; Barnes and Percival 2006; Broschat and Elliot 2009; Percival 2013).

Compost teas are liquids containing soluble nutrients and species of bacteria, fungi, protozoa, and nematodes extracted from compost. Compost teas are being used to enhance soil biology and provide nutrients, sometimes as an alternative to fertilization, but research support for their effectiveness is lacking (Scharenbroch et al. 2011).

Sucrose can increase root:shoot ratios by downregulating genes used for photosynthesis (Percival and Fraser 2005). Applied as a root drench, it enhanced root vigor when applied at up to 70 g/L in some studies (Percival 2004; Percival and Fraser 2005; Percival and Barnes 2007), but not others (Martinez-Trinidad et al. 2009). In most of these studies, the sugar was applied to the soil at least twice.

Healthy soils with favorable physical and chemical characteristics will support active soil biology naturally. Improving soil conditions is preferred over addition of compost teas, biostimulants, mycorrhizal fungi, and other means.

One of the most important soil functions is to serve as a medium for root growth. Physical, chemical, and biological soil characteristics all have an effect on tree roots. A thorough understanding of how these soil characteristics affect root growth is necessary to properly manage soils for optimum root growth. Although most urban soils are substantially altered from the natural state, or even completely manufactured, urban soils must still provide the necessary resources for root growth. Highly disturbed soils require very careful management to maintain conditions favorable for root growth. Management practices aimed at preventing soil damage or restoring aspects of the natural soil environment have the strongest research to support their effectiveness in improving root growth in urban and suburban settings.

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Zusammenfassung. Die physischen, chemischen und biologischen Zusammensetzungen von städtischen Böden enthalten oft Begrenzungen für das Wachstum von Wurzeln. Für ein gutes Management ist ein Verständnis für die Beziehungen der Bodenanteil sehr wichtig. Als ein Resultat dieser gegenseitigen Abhängigkeiten kann der Status eines Bodenfaktors alle anderen beeinflussen. Die Vermeidung von Bodenschäden ist sehr effektiv und erstrebenswert. Pflegemaßnahmen, wie Kultivierung und Mulchen können effektiv die Bodeneigenschaften verbessern. Zusätze für den Boden, wie Produkte zur Biostimulation, haben sich in der Forschung als nicht zuverlässig effektiv erwiesen. Die Herausforderung an das Management ist, eine urbane Umwelt zu liefern, die nahezu wie eine natürliche Umgebung funktioniert.

Resumen. Las restricciones físicas, químicas y biológicas de los suelos urbanos suelen plantear limitaciones para el crecimiento de las raíces de los árboles. La comprensión de las interrelaciones de las propiedades del suelo es importante para un adecuado manejo. Como resultado de la interdependencia de las propiedades del suelo, el estado de uno de los factores del suelo puede tener un efecto sobre todos los demás. La prevención de daños en el suelo es preferida; las prácticas culturales tales como el cultivo y el acolchado son apropiadas en la mejora de las propiedades del suelo. Los aditivos del suelo, tales como productos bioestimulantes, no han demostrado ser consistentemente eficaces a través de la investigación. El desafío del manejo es proporcionar un entorno urbano que funcione como el medio ambiente natural.