Tree Committee Meeting of the City of Spokane Park Board

Tuesday, March 31, 2015, 4:15 p.m. – 5:45 p.m.
Willow Room, Woodland Center
John A. Finch Arboretum
Angel Spell – Urban Forester

Committee Members:
X Pendergraft, Lauren – Chairperson
A Potratz, Preston
X Gifford, Guy
X Davis, Garth
A Cash, Kevin

Park Board:

Parks Staff:
Angel Spell

Guest(s):
Carrie Anderson
Nancy MacKerrow

Summary

- Updates were given on six grants currently in-progress or recently completed.
- Staff report was presented and discussed including year-to-date performance and upcoming events.
- The Citizen Advisory Committee Report was delivered and discussed; items included early appearance of the Ips bark beetle and a Ponderosa pine tree replacement policy.
- Angel presented a Research & Data Report which included metrics on the trees of Coeur d'Alene Park and two journal articles related to root systems in the urban environment.
- Urban Forestry Financial Report was unavailable.

MINUTES

The meeting was called to order at 4:20 p.m. by Chairperson, Lauren Pendergraft. Introductions were made.

Action Items:

None

Discussion Items:

1. Grants Update – *Angel Spell*

   Angel reported on the current status of six various grants, of which two are complete.

2. Staff Report – *Angel Spell*

   The progress-to-date of work done by Staff and upcoming events was presented and discussed. Also, the Utility Bill Donation Program has now been implemented online and funds have already been received. Angel expressed her appreciation for the success of the Arboretum Educational Series thus far this season. She also informed attendees of upcoming events.

   Inquiry concerning actions in response to past vandalism of neighborhood trees was discussed and the options provided by Spokane Municipal Code.

Standing Report Items:

3. Citizen Advisory Committee Report – *Guy Gifford*

   Ips bark beetles are already appearing on trees whereas historical appearance has been May. Ponderosa Pine replacement policy was discussed. Interest was also expressed to promote the value and benefits of Ponderosa Pine trees to improve public perception.

   The date has been confirmed for the High Drive hike; June 30th.

4. Research & Data Report – *Angel Spell*

   Coeur d'Alene Park has 373 trees having over $4 million in value. Friends of Coeur d'Alene Park are satisfied with Ponderosa Pine population (63%) in the park and accept that the ones in very poor health may be removed.

   Two research reports on tree root systems in the urban environment were distributed to the group for review and possible future discussions.

5. Urban Forestry Financial Report – *Angel Spell*

   No report available.

   Lauren provided information regarding the Letter of Understanding between the stormwater utility and Parks & Recreation. The amount has been established, but the percentage designated to Urban Forestry still needs to be determined.

Meeting adjourned at 5:24 p.m.

The next regularly scheduled meeting is May 5, 2015, 4:15 p.m., at Finch Arboretum in the Woodland Center's Willow Room.

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

Gary W. Watson, Angela M. Hewitt, Melissa Custic, and Marvin Lo

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; Ericsson 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.

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The Management of Tree Root Systems in Urban and Suburban Settings II: A Review of Strategies to Mitigate Human Impacts

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Abstract. Root systems of nearly all trees in the built environment are subject to impacts of human activities that can affect tree health and reduce longevity. These influences are present from early stages of nursery development and throughout the life of the tree. Reduced root systems from root loss or constriction can reduce stability and increase stress. Natural infection of urban tree roots after severing has not been shown to lead to extensive decay development. Roots often conflict with infrastructure in urban areas because of proximity. Strategies to provide root space under pavements and to reduce pavement heaving have been developed, but strategies for prevention of foundation and sewer pipe damage are limited to increasing separation or improved construction.

Key Words. Ground-Penetrating Radar; Infrastructure Damage; Root Architecture; Root Decay; Root Defects; Rooting Space; Root Flare; Root Severing; Stability.

Tree root systems are generally shallow and widespread (Day et al. 2010). Human activity around trees frequently impacts tree root systems, decreasing tree health and reducing longevity compared to trees on natural sites. Construction and repair of infrastructure often severs tree roots. The presence of buildings and pavements can restrict root systems with detrimental effects on both the tree and the structure. Urban landscape design and maintenance can be very different than the natural environment to which the trees are adapted. Root architecture is altered by nursery production and transplanting, which can affect the tree throughout its life. The management challenge is to avoid or reduce these impacts through proper management, including minimizing injury to existing roots, speeding root regrowth after severing occurs, and maximizing the quality and quantity of root space in design.

ROOT ARCHITECTURE AND STABILITY

Tree stability depends heavily on both root system architecture and the anchorage of roots in the soil. Root/soil resistance gives rise to the characteristic mass of roots and soil seen on uprooted trees, known as the root plate. The anchorage strength of a tree root system has four components: 1) the mass of the roots and soil levered out of the ground, 2) the strength of the soil and depth of root penetration under the root plate, 3) the resistance to failure in tension of tree roots on the windward side as the upward movement of the root–soil plate causes roots to pull out of the soil with or without first breaking, and 4) the length of the lever arm (where the roots hinge) on the leeward side, which is affected by root diameter and resistance to bending of the tree roots (Coutts 1983; Coutts 1986; Blackwell et al. 1990; Kodrik and Kodrik 2002). A change in one feature can affect several others. Thus, an increase in root plate diameter will increase the weight component, the length of lever arm between the trunk and the roots around the perimeter of the plate, and the area of root/soil contact under the plate. As each of these anchorage components increases, the greater the force needed to tip up the root plate. Uneven distribution (large sections without roots) reduces anchorage (Sundstrom and Keane 1999).

Environmental factors influence root architecture and stability. If roots penetrate deeper, as can be the case in sandy soil, the tap root and deeper roots have more influence on overturning resistance in sandy soil compared with clayey soil (Fourcaud et al. 2008). Wind loading appears to result in increased growth of lateral roots at the expense of the tap root. Development of the lateral root system may therefore ensure better anchorage of young trees subjected to wind loading (Tamasi et al. 2005).

Root branching shortens the root plate lever arm and makes tipping easier. The roots of nearly all trees in urban areas have been severed during transplanting, which creates branching at the cut end and smaller regenerated roots. This branching may shorten the root plate fulcrum on the leeward side and reduce the diameter of the roots at the perimeter of the root plate, with the possible effect of rendering urban trees less stable than their forest counterparts with less-branched, larger roots. However, no direct research on urban trees is available.

ROOT INJURY

Consequences of Root Severing

Analysis of published data on root spread of trees concluded that the radius of the root system is approximately equal to tree height (Day et al. 2010), which is often greater than the radius of the branches (drip line). Given the close proximity of trees to structures, pavements, and utilities in most urban and suburban landscapes, tree roots can be easily injured by soil excavation.

Root loss from severing can be considered temporary when roots are able to regenerate and eventually replace roots that were lost. If the root space is permanently lost (e.g., resulting from construction of a structure or pavement in the root zone), then the root system will not be able to replace itself, and stress and stability concerns may never be overcome.

Root loss from trenching can affect both tree health and stability. Trenching through the root zone of parkway trees was considered to be responsible for substantial tree dieback and decline over the following 12 years, and was the basis for development of auguring specifications in common use (Morell 1984). While generally accepted, the little research available has not been completely supportive.

When trenches were dug for installation of new utilities 0.5 to 3.3 m from hackberry (*Celtis occidentalis*), sweetgum (*Liquidambar styraciflua*), sugar maple (*Acer saccharum*), and honeylocust (*Gleditsia triacanthos*), only on hackberry, where the trench was only 0.5 m from the trunk (approximately 1.5 times the trunk diameter), was growth-reduced for all four growing seasons monitored following trenching. The trenching did not predispose the trees to readily evident disease or insect infestations (Miller and Neely 1993). If the trench was three times the trunk diameter away from the trunk, or more, no consistent growth reduction was measured. No growth reduction or dieback was reported when pin oak (*Quercus palustris*) trees were trenched on one or two sides at a distance of three times the trunk diameter. However, moderate dieback was noted on trees that were trenched on three sides (Watson 1998). Street or sidewalk construction at a distance of five to seven times the trunk diameter from the tree resulted in only a 4% increase in mortality and a 5% decrease in condition rating (Hauer et al. 1994).

Root loss reduces the capacity of the root system to absorb water, most of which is transpired through the leaves. Compensatory pruning along with severe trenching reduced dieback from stress but was most beneficial after the most severe root loss (Watson 1998). These trees did not receive any irrigation or special care, which could possibly have reduced dieback development even without pruning.

Hamilton (1988) suggested that some species may be more prone to uprooting after root pruning, based on observation. Stability of trees after the roots have been severed is a concern that has not been fully addressed by research. When trenches were cut alongside trees, tree anchorage was compromised by trenches only when closer than 2.5 times the diameter of the trunk on the tension side (Bader 2000; Smiley 2008b; Ghani et al. 2009). The surprisingly high anchorage of the trees with such severe root loss was thought to be because rooting depth close to the trunk was a major component of anchorage. Cutting roots on both sides of the tree reduced the force required to cause tree failure by two-thirds when trees were trenched simultaneously at five times the trunk diameter on the tension side and about half that distance on the compression side (approximate location of the root plate hinge point) (O'Sullivan and Ritchie 1993). Trees with asymmetrical or restricted root systems may be less stable after root severing.

These studies suggest that vigorous trees less than 30 cm diameter may be able to tolerate roots being severed on one side as close as three times the trunk diameter without a major loss in stability or crown decline. Larger trees, such as those on which the specifications were based, may be less tolerant. As surprising as it might seem that root severing did not kill any trees or cause severe dieback in these studies, consider that when roots are cut to form a root ball to transplant a tree, roots are cut on all sides at a distance of three to five times the diameter of the trunk (Anonymous 2004; Anonymous 2010). The trees are stressed, but even very large trees recover if cared for properly. Comparison of trenched trees in the established landscape to transplanted trees may be fairly realistic (Hamilton 1988).

Root Decay

Principles of Compartmentalization of Decay in Trees (CODIT, Shigo 1977) apply to roots as well as stems, although roots have not been studied as extensively (Shigo 1972; Shigo 1979a; Tippett and Shigo 1980; Tippett and Shigo 1981; White and Kile 1993; Robinson and Morrison 2001). Because root injuries are common and injuries serve as infection courts for root-rotting organisms (Tippett et al. 1982), roots have evolved to be strong compartmentalizers (Shigo 1986).

Average values of longitudinal extension of decay columns in roots of Sitka spruce (*Picea sitchensis*), white fir (*Abies concolor*), and Norway spruce (*Picea abies*) after artificial inoculation have been reported from 10 to 53 cm per year, (Morrison and Redfern 1994; Garbelotto et al. 1997; Piri 1998). Decay introduced experimentally through root wounds within a meter of the trunk can extend into the trunk (Redmond 1957; Garbelotto et al. 1997).

In contrast, the natural infection of landscape tree roots 3 to 22 cm in diameter after severing has not led to extensive decay development. Five to seven years after severing, decay extended no more than 10 cm from the severed end of roots of 7-year-old sweetgum (*Liquidambar orientalis* × *L. styraciflua*) and plane hybrids (*Platanus occidentalis* × *P. orientalis*) (Santamour 1985), or 40-year-old honeylocust (*Gleditsia triacanthos* var. *inermis*), pin oak (*Quercus palustris*), tulip-tree (*Liriodendron tulipifera*), and green ash (*Fraxinus pennsylvanica*) trees (Watson 2008). Trunk wood decay was observed only when the root cambium had died back to, or above, the soil surface and may have been the result of trunk injury (cambial death) rather than the root wounding (Santamour 1985). Although the number of research studies is limited, these results suggest that decay development as a result of severing roots is not an immediate threat to the health or stability of a tree.

Santamour (1985) also reported differences between species in their ability to resist trunk decay and discoloration after root severance. Four years after severing roots within 0.5 m of the trunk, there was no discoloration or decay in trunk tissues in red maples (*Acer rubrum*), and 6 cm maximum in the roots. Discoloration and decay was present in trunk tissues of 2 of 10 black oaks (*Quercus velutina*) and 4 of 10 white oaks (*Q. alba*) after similar root severance.

Root size and proximity to the trunk has been reported to affect decay development rate. Root decay increased as root size increased on hardwoods (Whitney 1967; Santamour 1985; Balder et al. 1995; Balder 1999) and conifers (Piri 1998; Tian and Ostrofsky 2007). Injury to roots close to the trunk resulted in more extensive decay on hardwoods (Shigo 1979b; Balder et al. 1995; Balder 1999). Other studies do not support these conclusions (Shigo 1991; Watson 2008). Injury of roots in the dormant season may lead to poorer compartmentalization and increased decay development, but reports are inconsistent (Santamour 1985; Balder et al. 1995; Balder 1999).

Stressing and limiting the development of roots, particularly constriction of root diameter growth, as results from certain root defects, predispose the roots to *Armillaria* infection (Livingston 1990). The increased success of infection by *Armillaria* sp. as a result of root severance appears to be associated with changes in the nutrient status of the roots after they have been damaged, rather than simply an increase in sites for penetration (Popoola and Fox 1996).

Trees that fail due to root decay under non-stormy conditions often have extensive decay in the root flare (roots forming the curvature between vertical trunk and the angled structural roots, also known as buttress roots). Decay can develop on the lower side of major flare roots, where it can remain undetected. Drilling is recommended to determine the amount of sound wood. Major flare roots are considered significantly decayed if the thickness of the sound wood on the root is less than 0.15 times the tree diameter (Fraedrich and Smiley 2002). Thermography can be effective in approximating the decayed areas of the root collar (Cellerino and Nicolotti 1998; Catena 2003).

Locating Roots

Locating roots prior to construction to avoid damaging them is time-consuming and expensive if done with hand digging. Introduction of air excavation tools has made the task considerably more efficient (Nadezhdina and Cermak 2003). Non-destructive, ground-penetrating radar can be used to map larger roots. Roots 1.0 cm diameter and larger, and as deep as 2 m, can be detected (Hruska et al. 1999; Cermak et al. 2000; Butnor et al. 2001; Butnor et al. 2003; Nadezhdina and Cermak 2003; Barton and Montagu 2004). Vertical roots and roots with less than 20% water content could not be detected by ground-penetrating radar (Stokes et al. 2002; Hirano et al. 2009). Two roots located closely together cannot be individually distinguished (Hirano et al. 2009; Bassuk et al. 2011).

Resolution of roots may be best in sandy, well-drained soils, whereas soils with high soil water and clay contents may seriously degrade resolution and observation depth (Butnor et al. 2001). Interference from other objects present in the soil was sometimes found to be a problem in early ground-penetrating radar studies (Cellerino and Nicolotti 1998; Hruska et al. 1999). Ground-penetrating radar was effective in structural soil, which is 80% stone (Bassuk et al. 2011). Roots could be mapped under concrete and asphalt (Nadezhdina and Cermak 2003; Bassuk et al. 2011). Development of software to reconstruct 3D images of root system architecture from raw data may still need improvement (Stokes et al. 2002).

Root Regeneration

Root severing can increase the rate of root growth on one-year-old seedlings or rooted cuttings, but the more rapid root production merely compensates for the roots removed (Abod and Webster 1990). The potential for water uptake is proportional to the number of new roots produced (Carlson 1986).

When woody roots are severed, numerous new roots are initiated at, or just behind, the cut (Wilcox 1955; Carlson 1974; Watson and Himelick 1982a; Gilman et al. 2010). However, a portion of regenerated roots can originate from at least 10 cm behind the cut, depending on species (Gilman and Yeager 1988). The ability of damaged roots to form new roots decreased with increasing diameter (Balder et al. 1995; Balder 1999). When a root is severed, new roots that formed nearest to the cut surface will elongate in the same direction as the original root. New roots forming slightly behind the cut surface tend to grow at more perpendicular angles to the original root (Horsley 1971).

Initiation of new roots from severed palm roots varies with species and distance from the base of the trunk (Broschat and Donselman 1984). Less than one percent of all cut cabbage palm (*Sabal palmetto*) roots regenerated root tips, whereas coconut palms (*Cocos nucifera*) regenerated root tips about 50% of the time regardless of root stub length. For other species of palms, such as queen palm (*Syagrus romanzoffiana*), royal palm (*Roystonea regia*), Mexican fan palm (*Washingtonia robusta*), and Senegal date palm (*Phoenix reclinata*) the percentage of roots surviving increases with stub length (Broschat and Donselman 1984; Broschat and Donselman 1990a). Cutting palm roots at least 30 cm from the trunk will ensure better survival of existing roots (Broschat and Donselman 1990a).

Auxins are commonly used to promote rooting in stem cuttings and can increase the number of new roots initiated near the cut ends of roots. Indole-3-butyric acid (IBA), indole-3-acetic acid and naphthaleneacetic acid applied to roots resulted in increased root initiation (Gossard 1942; Verzilov 1970; Lumis 1982; Magley and Struve 1983; Prager and Lumis 1983; Struve and Moser 1984; Fuchs 1986; Watson 1987; Al-Mana and Beattie 1996; Percival and Gerritsen 1998; Percival and Barnes 2004), but may reduce root elongation (Struve and Moser 1984; Percival and Barnes 2004). Addition of 5% sucrose to the auxin solution enhanced the results (Fuchs 1986). Verzilov (1970) reported increased root growth into the third season after application but was unsure if it was a residual effect of the auxin application or resulted from greater tree vigor after the initial increase in root growth. IBA treatment did not increase root initiation of palms (Broschat and Donselman 1990b).

The rate of new root initiation is affected by the environment. At near-optimum soil temperatures, new root growth was detected in 4 to 43 days depending on species (Howland and Griffith 1961; Arnold and Struve 1989). Intact root tips began to elongate before new roots were initiated (Arnold and Struve 1989). Total new root length was positively correlated with soil temperature with significantly more new root growth at 20°C (Andersen et al. 1986). Tree fine-root growth was slowed by approximately half when soil temperatures dropped from 20°C to 10°C (Tyron and Chapin 1983). When roots are severed late in autumn, after soils have cooled, substantial new root growth may not occur until the soils have warmed again in the spring. In warmer regions, active root growth may continue all winter. Plants that were slightly drought-stressed prior to severing roots had greater root regeneration (Abod and Sandi 1983), but decreased soil moisture after severing significantly reduced root regeneration (Witherspoon and Lumis 1986). Plants supplied with adequate (non-deficient) nutrients before transplanting had a high capacity to regenerate roots following root severing (Abod 1990).

Annual root extension depends on species and annual soil temperature regime. In the upper Midwestern United States (USDA Hardiness Zone 5), with its moderate summers and frozen soils in winter, roots grow at an average annual rate of approximately 50 cm (Watson 1985; Watson 2004). In one season under nursery conditions in Hardiness Zone 6, red oak (*Quercus rubra*) roots grew 53–61 cm (Starbuck et al. 2005) and birch (*Betula pendula*) roots grew 89 cm (Solfjeld and Pedersen 2006). In the subtropical climate of north central Florida (Hardiness Zone 9), where the growing season is nearly year-round, annual root growth is up to 2 m or more for some oak (*Quercus*) and citrus species that have been studied (Castle 1983; Gilman 1990; Gilman and Beeson 1996). As the roots continue to increase in length, fine roots continue to increase in density for up to five years (Hutchings et al. 2006).

Root growth for some species will be higher or lower than average figures. For example, black maple (*Acer nigrum*) roots grew 39 cm in a season in the midwestern United States, which is near the expected average. Under the same conditions, green ash (*Fraxinus pennsylvanica*) grew nearly twice as much, 67 cm (Watson 2004). In general, it may require many years to replace the roots lost when they are severed.

Fine-Root Desiccation

There is sometimes concern that fine roots subject to drying by excavation will be damaged. Desiccation of little-leaf linden (*Tilia cordata*), green ash (*Fraxinus pennsylvanica*), and sugar maple (*Acer saccharum*) fine roots had no effect on root regeneration (Witherspoon and Lumis 1986; Watson 2009), though moisture content was reduced by as much as 80% (Watson 2009). In contrast, root growth of wild cherry (*Prunus avium*) and cherry plum (*P. cerasifera*), and of noble fir (*Abies procera*) seedlings, was reduced after desiccation treatment (Symeonidou and Buckley 1997; Bronnum 2005). Susceptibility of fine roots to damage from desiccation may be species dependent.

ALTERATION OF ROOT STRUCTURE

Root structure and tree growth rate are closely related. For conifers (*Picea* sp., *Abies* sp., *Pinus taeda*) and hardwoods (*Quercus* sp., *Liquidambar styraciflua*, *Juglans nigra*) studied, when one-year-old seedlings are sorted by root morphology, individuals with a high number of laterals consistently have greater growth after planting (Kormanik 1986; Ruehle and Kormanik 1986; Kormanik 1988; Kormanik et al. 1989; Schultz and Thompson 1997; Kormanik et al. 1998; Gilman 1990; Ponder 2000). Little information is available on how long this increased growth persists, but large forest trees that have out-competed their weaker neighbors over a lifetime typically have many visible flare roots.

Structural Root Depth

The large woody roots giving characteristic form to the root system are commonly referred to as structural roots (Sutton and Tinus 1983). These roots can be too deep for many reasons. Roots of young trees can be too deep because nursery production systems can increase structural root depth. Pruning the primary (tap) root of seedlings early in the production of field-grown nursery stock produces adventitious roots at the cut end of the primary root that grow rapidly (Johnson et al. 1984; Harris et al. 2001; Hewitt and Watson 2009). Up to 60% of the natural lateral roots that would normally develop into flare roots located above the regenerated roots may be lost (Hewitt and Watson 2009). The vigorously growing adventitious roots at the cut end, and loss of natural lateral roots above them, often replace the natural root flare (swelling where roots join the trunk also known as the trunk flare) with an "adventitious root flare" deeper in the soil. The depth of the adventitious root flare is determined by the length of the primary root after pruning (root shank). Even if the tree is planted at the original depth with the graft union visible aboveground, the adventitious root flare can be 30 cm or more below the soil surface. Other practices, such as burying the graft union below the soil surface and certain cultivation practices, can also contribute to root depth. Young trees can be more susceptible to being blown over by high winds when depth to the first root is excessive (Lyons et al. 1982).

The structural roots can also be too deep in container-grown nursery stock if trees are not planted carefully at each repotting. A dense mat of roots can fill the soil above the woody roots that form the root flare (Fare 2006; Gilman and Harchick 2008; Gilman et al. 2010b), and make it impossible to plant the woody roots at the correct depth without cutting away a substantial portion of the roots in the ball.

Though trees may grow well enough in the well-drained substrate of the container or high-quality soil of the nursery field, they may struggle to survive when planted on difficult urban sites with heavy soils and poor drainage (Switzer 1960; McClure 1991; Day and Harris 2008). The consequences may not be seen immediately. Regenerated roots can grow back to the surface (Day and Harris 2008), but the root collar will always be too deep. Dramatic improvements in tree condition have been attributed to root collar excavation in practice (Smiley 2006). In the only published research study, street trees failed to show any influence of root collar excavation on tree growth over a four-year period (Rathjens et al. 2009).

Root systems of established trees can become deeper when fill soil is added over them. Research has not been able to consistently show detrimental effects on trees, though reports from practice attribute poor performance and *Armillaria* and *Phytophthora* infections to deep roots and soil against the trunk (Smiley 2006). After three years, there was no consistent effect of 20 cm of C horizon fill on overall root density, growth, or soil respiration. Fill did disrupt normal soil moisture patterns (Day et al. 2001). After approximately ten years, the fill still had no effect on trunk diameter growth. Bark of some oak trees appeared to be decaying, but bark biopsies revealed only saprophytic fungi (Day et al. 2006). A "collar rot" caused by a *Phytophthora* sp. and a "basal canker" caused by *Fusarium* spp. were associated with buttress roots of planted maples that were deeper than roots of natural, woodland maples (Drilias et al. 1982).

Installation of subterranean piping systems or core venting systems to counter the adverse impact of fills is sometimes recommended (Harris et al. 1999). Studies of aeration pipes installed prior to addition of fill have been inconclusive. With or without pavement-like surface cover, conditions under fill were not severe enough for any "improved" effect to be measured from the use of an aeration system. Greater trunk growth in plots with aeration pipes was attributed to increased soil moisture in the plot with aeration pipes (MacDonald et al. 2004; Townsend et al. 1997). These results underscore the need for further quantitative studies of conditions created by various fill and paving procedures to better ascertain the usefulness of elaborate and expensive aeration systems. Other factors associated with raising the grade, such as soil trafficking and root severance, may be responsible for much of the tree decline attributed to fill.

A layer of crushed rock over existing soil before filling with clay soil increased oxygen (percent) and reduced carbon dioxide in the soil beneath it compared to a comparable area where no crushed rock was used before clay fill was placed over the soil surface (Yelenosky 1964).

Circling Roots

Growing trees in nursery containers alters natural root structure (Halter et al. 1993). Reports are rare of adventitious roots developing above the circling, kinked, or twisted form found within the container root ball after planting (Gilman and Kane 1990).

Circling roots on the surface of the container root ball are widely recognized as a defect and it is common practice to disrupt these by making several vertical cuts, or "slashes," on the outside of the root ball before planting (Ellyard 1984; Blessing and Dana 1987; Arnold 1996; Gilman et al. 1996). Methods that disrupt circling roots do not eliminate descending, ascending, and kinked roots. Containers designed to prevent circling often direct roots contacting the wall down to the bottom or up to the surface. Root deformities often become a permanent part of the root system (Grene 1978).

Root ball "shaving" is cutting off the outer surface of the root ball to remove all roots on the root ball surface. It results in a root system with roots growing more radially from the trunk (Burdett 1981; Gilman et al. 2010). Root growth after planting trees from containers without shaving was one-quarter of that of field-grown trees and resulted in reduced tree stability (Gilman and Masters 2010). Growing plants in $CuCO_3$-treated containers resulted in the reduced defects after planting in the landscape (Burdett 1978; Arnold and Struve 1989; Arnold 1996).

Girdling Roots

Girdling roots have a different origin than circling roots caused by production containers and can be a significant problem for at least some species of trees planted as field-grown stock. Norway maples (*Acer platanoides*) frequently had severely girdling roots as mature trees (Watson et al. 1990; Wells et al. 2006). All 50-year-old Norway maples (*Acer platanoides*) had one to nine girdling roots. There was no grafting between girdling roots and trunks (Tate 1980). Girdling roots and potentially girdling roots were more common on sugar maple (*Acer saccharum*) and red maple (*Acer rubrum*) than on green ash (*Fraxinus pennsylvanica*), honeylocust (*Gleditsia triacanthos*), littleleaf linden (*Tilia cordata*), and Yoshino cherry (*Prunus × yedoensis*) trees, 2 to 10 years after planting.

The majority of the girdling roots can be either small, existing laterals when transplanted, or new laterals initiated during the first year after transplanting. Lateral roots at perpendicular angles, close to the base of the trunk, are naturally positioned to develop into girdling roots. Growth of these lateral roots is often slow while the root terminal is intact, but can be stimulated when the terminal is severed as the tree is dug from the nursery. Further evidence that girdling roots result from transplanting is provided by the low incidence of girdling roots found in nature (Watson et al. 1990).

Girdling roots have been associated with excessive soil over the root system (d'Ambrosio 1990; Giblin et al. 2005; Wells et al. 2006), though not always (Watson et al. 1990). One report hypothesized through observation that girdling roots are associated with low dense crowns creating cool and moist conditions at the base of the tree (d'Ambrosio 1990).

Cross-sectional area of vessels in stem xylem affected by the girdle was only 10% that of unaffected wood. Rays in stem wood were skewed and contained few pits. Bark on girdled stems was compressed from a normal thickness. The offending roots sustained slight compression of cells where in contact with the stem and appeared to remain functional. Thus, girdling roots apparently cause tree decline by reducing stem conductivity and radial communication between tissues (Hudler and Beale 1981).

Girdling roots do not always cause rapid decline or death of trees. Aboveground decline symptoms of girdling roots include gradual shortening of terminal growth, small leaves, early autumn color, dieback of branches in sections of the canopy, and partial or total absence of a root flare (Gouin 1983; Holmes 1984). A survey of 416 urban Norway maples (*Acer platanoides*) found that although 336 had girdling roots, most girdling was minor and did not lead to visible decline of the trees (Tate 1981). Red (*Acer rubrum*) and sugar maples (*Acer saccharum*) artificially girdled with angle iron to simulate a girdling root on one side, remained alive for seven to eight years, but Norway maples engulfed the girdling devices and were alive after 17 years (Holmes 1984).

Treatments consisting of cutting girdling roots, fertilizing, and pruning foliage were evaluated after two years and did not alleviate aboveground symptoms (Tate 1980). Removal of potential girdling roots resulted in a detrimental effect on twig extension (Rathjens et al. 2009). Removal of girdling roots as an early corrective treatment on young Norway maple trees did not eliminate them. Multiple roots reformed from the wound site where a single girdling root had been removed. Despite this lack of validation by research, girdling root removal continues to be a common practice. The best hope for eliminating girdling root problems may be to develop root stock from trees without girdling roots (Watson and Clark 1993).

Girdling by wires of the wire baskets used to support root balls during shipping and handling is a similar situation. Studies with wires girdling stems of young trees showed no detrimental effect of girdling (Goodwin and Lumis 1992). Examination of roots contacting wires 11 years after planting found that root tissues reunited after closing around the wire and there was complete union of vascular tissue beyond the wire (Lumis and Struger 1988). The small diameter of the wires may pose less of a threat than larger roots similarly positioned.

Root Grafts

Root grafting can be beneficial or detrimental to trees, depending on the circumstances. When root grafts between individuals of the same species occur, the grafts allow passage of solutes through the connecting xylem (Graham and Bormann 1966; Jane 1969). Girdled trees with no transport of carbohydrates from the crown to the root system can survive for years if their roots are supported through grafts to roots of neighboring trees (Stone 1974).

Root grafts among groups of elms were considered responsible for more than 50% of Dutch elm disease disease transmission when the disease was at its peak in U.S. cities (Cuthbert et al. 1975). Oak wilt is also commonly transmitted through root grafts (Gibbs and French 1980; Appel 1994). In both situations, disrupting root grafts is an important method of disease control. Both mechanical and chemical methods of severing roots have a long history (Himelick and Fox 1961; Neely and Himelick 1966), with more recent variations tested (Wilson and Lester 2002).

INFRASTRUCTURE–ROOT CONFLICTS

Pavement Conflicts

When pavements are laid on a compacted soil base, roots often grow in the gap between the pavement and the compacted soil under it. Moisture is high because the pavement prevents evaporation, and condensation can form beneath the pavement as it cools (Kopinga 1994a; Kopinga 1994b; Wagar and Franklin 1994). Aeration can be adequate, especially under narrow pedestrian sidewalks (Kopinga 1994a; D'Amato 2002a). Roots enlarge and can eventually lift and crack the pavement. Species that have a small number larger roots could cause considerably more damage than if the same biomass were allocated between larger numbers of smaller roots (Nicoll and Coutts 1997).

Potential for conflicts between trees and pavement is high when one or more of the following factors are present: tree species that are large at maturity, fast growing trees, shallow rooting habit, trees planted in restricted soil volumes, shallow topsoil (hardpan underneath topsoil), limited or no base materials underneath the sidewalk, shallow irrigation, distances between the tree and sidewalk of less than two to three meters, or trees greater than 15 to 20 years old (Wong et al. 1988; Randrup et al. 2003). Large trees in restricted planting spaces is most commonly associated with pavement damage (Barker 1983; Wagar and Barker 1983; Wong et al. 1988; Francis et al. 1996; Achinelli et al. 1997; McPherson 2000; D'Amato et al. 2002b; Reichwein 2002; Reichwein 2003).

Research has challenged the common assumption that sidewalk pavement cracks near roots are always caused by the roots. Sidewalk damage can result from soil conditions and age of pavement as well as from tree roots. Older sidewalks failed more often. Sidewalks did not fail at higher rates where trees were present (Sydnor et al. 2000). With no roots present, 61% of all pavement expansion joints were also cracked (D'Amato et al. 2002a). Roots were more likely to be found under a cracked expansion joint in the sidewalk than under an uncracked joint, but the cracks may actually be contributing to roots growing under sidewalk pavements. Sidewalks that fail may allow more root growth beneath the cracks due to increased oxygen in the soil (Sydnor et al. 2000; D'Amato et al. 2002a).

Barriers are sometimes installed to prevent root growth under pavement. Barriers have been constructed from plastic, metal screening, and geotextile impregnated with herbicide. Most are effective at blocking roots between the surface and the bottom of the barrier if installed correctly. Differences in products have sometimes been reported in the first few years, but may not persist with time (Smiley et al. 2009).

Installation of root barriers reduces the number and diameter of roots and causes them to grow deeper for a limited distance on the far side. This has been reported consistently, and in both poorly drained (Wagar 1985) and well-drained and well-aerated soils (Gilman 1996; Costello et al. 1997; Nicoll and Coutts 1998; Peper 1998; Peper and Mori 1999; Smiley 2005; Pittenger and Hodel 2009; Smiley et al. 2009). After they grow under the barrier, roots do grow back toward the surface within a short distance from the barrier, but may remain deeper long enough to reduce pavement damage.

The effectiveness of barriers may not be permanent, since pavement damage by 30-year-old sweet cherry (*Prunus avium*) roots was associated with large roots as deep as 40 cm below the pavement (Nicoll and Armstrong 1997; Nicoll and Armstrong 1998).

Depth and installation of the barrier is important. A 45 cm deep barrier reduced roots under the pavement (Smiley 2008a) while a 30 cm barrier of similar design did not (Gilman 2006). Barriers need to be installed with the uppermost edge above grade. If roots are able to grow over the top of the barrier because of incorrect installation, deterioration of the exposed barrier material, or mulching over the barrier, can result in significant damage to pavements (Smiley 2008a; Tworkoski et al. 1996).

Barriers can reduce overall root development of trees (Wagar and Barker 1993; Barker 1995a; Gilman 1996; Smiley et al. 2009), but in most studies, no effect on trunk diameter growth was reported (Barker 1995a; Barker 1995b; Tworkoski et al. 1996; Costello et al. 1997; Peper 1998; Peper and Mori 1999; Gilman 2006; Smiley 2008a).

There is no evidence that root barriers will decrease stability. Slightly more force was required to pull over trees within root barriers. The increased stability was attributed to deeper roots (Smiley et al. 2000). The situation may be different if roots are not able to grow under the barrier, such as on sites with very poor soil aeration or very deep barriers. In such a situation, the limited root system on one or more sides could result in increased instability.

Other alternatives to root barriers have proven to be effective in preventing roots from growing beneath pavements and causing cracking and lifting. Extruded polystyrene foam 10 cm thick installed directly under poured concrete forced roots to grow under the foam. The expanding roots crushed the foam instead of heaving the pavement (Smiley 2008a).

When pavements were laid on a base of coarse gravel or brick rubble, the coarse material was apparently not a suitable environment for root growth between the stones, and the roots grew in the soil underneath it. Thicknesses of 15 cm and 30 cm were somewhat more effective than 10 cm (Kopinga 1994a; Gilman 2006; Smiley 2008a).

A 10 cm thick layer of structural soil beneath the pavement is not the intended use of structural soil, but has been used in place of gravel in practice (Smiley 2008a). Whereas the use of gravel discouraged root growth, a similar 10 cm deep layer of structural soil allowed vigorous root growth in the soil between the coarse stones, as it is designed to do. Roots in the stone layer resulted in extensive pavement cracking and lifting. When structural soils are used with a minimum depth of 60 cm, or a preferred depth of 90 cm, roots grew to the full depth of the structural soil and were not found exclusively at the surface (Grabosky et. al. 2001).

Certain root barrier products that are impregnated with herbicides to reduce root growth can be effective as root barriers, but raise concerns that mycorrhizae could be affected. Sweetgum (*Liquidambar styraciflua*, endomycorrhizal) and pin oak (*Quercus palustris*, ectomycorrhizal) root mycorrhizae collected from within 1 cm of a chemically impregnated barrier were unaffected in the only reported study (Jacobs et al. 2000). (For an extensive review of root barrier research, see Morgenroth 2008.)

Just as disease resistance is the preferred way to control a tree disease, developing trees with deeper root systems would be the best way to reduce pavement damage. Research has shown that root systems of certain tree species that often cause sidewalk damage [e.g., shamel ash (*Fraxinus uhdei*), zelkova (*Zelkova serrata*), Chinese pistache (*Pistacia chinensis*)] can be selected for deep rooting patterns. Unfortunately, when these trees were propagated by rooting cuttings; the propagated trees did not exhibit the same deep-rooting characteristic (Burger and Prager 2008).

Sewer Pipe Intrusion

Tree root intrusion into sewer systems can be a substantial problem. Tree roots rarely damage pipes, but Mattheck and Bethge (2000) hypothesize that when a tree root encircles a pipe, wind loading may result in enough movement to break the pipe, especially when this occurs near material defects.

Roots can enter pipes in breaks and loose joints and then proliferate rapidly once inside the moist, nutrient-rich environment. Older pipes have more root intrusions because of age and materials used. Clay and concrete pipes without rubber gaskets in the joints resist root intrusion the least. The most intrusions have been into the smaller dimension pipes, 22.5–40 cm, possibly because the larger pipes are usually deeper in the soil and the roots may not reach them as easily. Sandy soils are more easily penetrated by roots reaching pipes. In poor growing conditions, the roots seek their way into the pipes relatively quickly, while in good growing conditions the process is considerably slower. In general terms, full-grown trees that have a large crown volume and thus a high requirement for water during the growing season have the greatest potential to cause large-scale damage to sewage systems by root intrusion. Certain tree species, such as poplar (*Populus*), willow (*Salix*), Melaleuca (*Melaleuca*), and Eucalyptus (*Eucalyptus*) are more likely to cause root intrusion. Tree size and proximity to the sewer pipe are also factors (Stål 1992; Lidstrom 1994; Rolf and Stål 1994; Stål 1995; Pohls et al. 2004; Ridgers et al. 2006).

Herbicides have been used to control root growth in sewer pipes. Metam-sodium and dichlobenil in combination is the most common. Metam-sodium is non-systemic and does not move throughout the root system, killing the whole plant. Dichlobenil is used with metam-sodium because it is an effective growth inhibitor. Air-aqueous foam is more effective than an aqueous mixture. The amount of chemical used in the foam application is small. Rapid breakdown of the metam-sodium and dilution of the product in the wastewater minimize environmental impacts, but use is still restricted in many areas (Ahrens et al. 1970; Leonard and Townley 1971; Leonard et al. 1974; Prasad and Moody 1974; Pohls et al. 2004).

Strategies to combat root intrusion are limited. Tree roots are less likely to grow into sewer pipes if planted 6 m or more from existing pipes. Slower-growing species with less aggressive root systems are best. Pipe construction can reduce intrusion by using longer pipe segments with fewer joints and proper installation (Rolf et al. 1995; Stål 1998; Randrup 2000).

Foundation Damage

Tree roots have been associated with interference with building foundations but rarely cause direct damage. Force from roots increasing in diameter is small, and damage only occurs to lightly loaded structures (Day 1991; Macleod and Cram 1996).

Roots in the vicinity of shallow foundations on soils with a high shrink-swell capacity can contribute to soil moisture depletion during drought, causing the soil to shrink and the building foundation to settle and crack (Day 1991). Records in England show that the incidence of failure of foundations on shrinkable clay soils is greater by a factor of ten than on other soils (Pryke 1979).

Tree genera vary in the amount their root systems can spread and contribute to building subsidence. [Roots cannot be reliably identified to species through anatomical features (Cutler et al. 1987).] The distance between damaged foundations and the tree with roots contributing to the damage was recorded for over 11,000 trees in the Kew Tree Root Survey. The average distance at which foundation damage was recorded varied from 2.5 m for cypress (*Cupressus*) to 11 m for poplar (*Populus*) with damage from most species occurring between 5 m and 7 m (Cutler and Richardson 1989). Depth of water extraction by roots may be restricted by soil conditions. Sharp changes in water and air permeability retarded rooting and water extraction beyond the upper 0.5 m of soil (Misra and Sands 1993). Species such as ash (*Fraxinus*), with relatively poor stomatal control of water loss, may accelerate soil drying, and therefore shrinkage (Stewart and Sands 1996).

Coutts (1979) suggests that since roots will grow where conditions are most favorable, and urban landscapes often have pavements and other features that restrict root growth in areas away from buildings, the most favorable soil may be between the tree and the building.

Control of roots with barriers is not considered an acceptable solution. Roots can grow under or over the barrier if not properly installed (as previously stated), or through cracks that may develop over time (Marshall et al. 1997). When roots are deflected laterally, there is a tendency to resume the original direction of growth once past the barrier (Wilson 1967), unless the barrier is long (Riedacker 1978).

Pruning is ineffective in controlling water use. Crown thinning did not reduce total tree water use or soil drying. A crown reduction of over 70% by volume affected water use for only a single season (Hipps 2004). The only way to ensure that there will not be a recurrence of the subsidence event after repair is to remove the tree (O'Callaghan and Kelly 2005).

Two solutions to the problem are to plant the tree well away from the structure or to use deepened perimeter footings to restrict roots from gaining access beneath the foundation (Day 1991). A combination of these is employed in the British National House Building Council guidelines, which provide recommendations based on shrinkability of the soils, the depth of the foundation, and the water demand and mature height of the tree. On a highly shrinkable soil, if a high water demand tree is located a distance equal to its height away from the foundation, the foundation should be 1.5 m deep. At half of that distance, a 2.5 m deep foundation is recommended (Biddle 1998).

ROOT SPACE REQUIREMENTS

When trees are planted in paved areas, the limited root space available in planting pits will ultimately limit the size and longevity of the tree (Fluckiger and Braun 1999). Average tree life expectancy in a sidewalk pit can be as little as ten years (Kopinga 1991; Nowak et al. 2004). Root restriction can reduce shoot elongation and decrease root dry weight:leaf area ratio. Imbalanced root:shoot ratios caused the development of internal water stress and plant senescence (Tschaplinski and Blake 1985; Vrecenak et al. 1989; Rieger and Marra 1994; Ismail and Noor 1996).

Crown spread and trunk diameter of trees growing in parking lots is reduced as surface area of nonpaved surfaces is reduced (Grabosky and Gilman 2004). Ninety-six percent of parking lot trees with at least 28 m^3 of soil were in good condition, compared to only 60% in less than 14 m^3 of soil. However, over 80% of the trees had been planted in the last 12 years (Kent et al. 2006), and condition of trees is likely to deteriorate as the trees grow and reach the limits of even the most generous root space.

Soil Volume and Quality

Variables to consider when determining how much root space is needed includes the quality of the soil present (water and nutrient storage capacity), how much evaporation and transpiration is expected, and how often the tree will receive rainfall or irrigation. As a general guideline for temperate climates, if above- and belowground environmental extremes are not severe, the root space recommendations vary from 0.15 to 0.7 m^3 of soil for each square meter of crown projection area of the expected mature size of the tree (Kopinga 1985; Lindsey and Bassuk 1991; Lindsey and Bassuk 1992; Urban 1992; Urban 2008). Similar estimates have not been developed for arid and semi-arid climates.

A computer model has been developed that uses climatological data to estimate the soil volume necessary to provide moisture in growing conditions likely to be encountered for an area. The example used is New York City, New York, U.S., with a 6 m crown diameter tree and 17 m^3 of soil, as recommended by Lindsey and Bassuk (1991). The tree, without irrigation, would face a water deficit every other year. With 27.4 m^3 of soil the tree would face a deficit only once in 10 years, but with only 4.3 m^3 of root space soil, the tree would need irrigation every fifth day to face a deficit only once in 10 years (DeGaetano 2000). Using a different method, Blunt (2008) calculated that under UK weather conditions, a mature tree (size and species not specified) would require at least 50 m^3 of high-quality soil with soil moisture recharged by rainfall or irrigation ten times during the growing season to avoid drought stress.

When soil volume is restricted, soil quality becomes very important. High-quality soil and intensive maintenance can compensate for limited root space volume to a limited extent. When soil was amended with organic matter to 60 cm depth, root development was greater than when just the upper 15 cm was amended (Smith et al. 2010).

It is generally accepted that when soil volumes are combined and shared by several trees, the performance of the trees seems to be better than when trees are in several smaller, individual planting pits of the same total volume. Research to support this observation is limited. Condition of live oaks (*Quercus virginiana*) was better in shared planting spaces but not lacebark elm (*Ulmus parvifolia*) or red maple (*Acer rubrum*). Maples performed poorly in all root spaces, and other factors may have been more limiting than shared root space. The elms performed well even in very limited, non-shared root spaces and may be less sensitive to small root spaces (Kent et al. 2006).

Expanding Root Space

Soils under pavements can be very difficult for root growth. The pavement itself can have mixed effects on the root environment beneath it. Soil moisture can be greater under pavement than surrounding unpaved areas because of reduced evaporation (Hodge and Boswell 1993; Arnold and McDonald 2009). Maximum summer soil temperatures under pavement exposed to sun can be up to 10°C warmer than nearby unpaved areas and exceed levels that injure tree roots (Halverson and Heisler 1981; Graves and Dana 1987). The soil compaction necessary to support stable pavement often restricts root growth. Several approaches have been used to provide suitable conditions for root growth under pavements without compromising stability of the pavement.

Pervious Paving

It has been suggested that pervious paving materials could improve the soil environment beneath pavements for better tree growth, but research has not yet shown this to be consistently true. Soil oxygen was insufficient for root growth (less than 12% oxygen) for prolonged periods beneath two of five pervious paving products tested on park footpaths (Couenberg 2009). Differences in soil oxygen and moisture between impervious and pervious concrete pavements are inconsistent (Morgenroth and Buchan 2009; Viswanathan et al. 2011). Pervious concrete plots had greater soil moisture in deeper layers in some seasons, but not in summer when it would be most beneficial, and there was no difference in tree growth rates, leaf water potential, or gas exchange (Volder et al. 2009). The narrow pavements (less than 1.5 m wide) used in these studies may allow water and oxygen to diffuse under the pavement from the edges of the solid pavement, just as effectively as through the pores of the pervious pavement.

To function correctly, pervious concrete pavement systems must have underlying soil that percolates well, which should also be beneficial for roots. If soil beneath the porous pavement is too compacted, the resulting poor soil aeration and penetration resistance are more likely to factor in limiting tree performance than the pavement (Viswanathan et al. 2011).

Structural Soils

Soils designed to support pavement without settling are often called load-bearing, skeletal, or structural soils. To expand root space under pavement in this way, the soil must provide a favorable environment for root growth while supporting the pavement.

The first soil of this type developed was called Amsterdam Tree Soil. Specifications call for 91%–94% medium coarse sand, 4%–5% organic matter, and 2%–4% clay (by weight). Phosphorous and potassium are added as necessary. The organic matter provides a source of nitrogen (Couenberg 1993). The soil mix is carefully compacted to a 70%–80% Proctor density when installed, and aeration is provided through spaces in the pavers placed over the soil. Callery pear (*Pyrus calleryana*) trees grew almost twice as rapidly in Amsterdam Tree Soil compared to standard pavement construction, and 50% faster than those grown in grass (Rahman et al. 2011).

Stone–soil mix structural soils create a network of interconnected spaces between the stones that can be filled with soil for root growth. When mixed and installed properly, structural stone-soil mixes compacted to 1.85 g cm^{-3}, and greater, and did not reduce macropore space or restrict root penetration in the soil between the stones (Grabosky and Bassuk 1996; Grabosky et al. 2009). In a container study, structural soil held 7%–11% moisture by volume, similar to a loamy sand, and had high infiltration and good drainage and aeration (Grabosky et al. 2009), but no field measurements have been reported.

Early tests of structural soil mixes in containers showed that stone–soil mixes could support better root and top growth than compacted soils or typical road base materials (Grabosky and Bassuk 1995; Kristoffersen 1999). Growth was limited by net soil volume rather than the total volume of the stone–soil mix (Loh et al. 2003). The root:crown ratio was greater in stone mixes than topsoil alone, indicating a larger root system was needed for absorption of water and nutrients when the soil was spread out in the mix (Kristoffersen 1999).

Results of field studies have been mixed. At three and ten years after installation, growth (DBH, height, canopy width) of trees planted in structural soil under pavement was equal to trees planted at the same time in a lawn adjacent to the sidewalk (Grabosky et al. 2002; Grabosky and Bassuk 2008). However, the trees planted in structural soil were within a few feet of an adjacent open-lawn area and the possibility that their roots may have grown into that soil volume was not addressed in the report. Other reports show that trees planted in non-compacted soils in open planters (Bühler et al. 2007) or covered by suspended pavement (Smiley et al. 2006) will outperform structural soil mixes. Stone–soil mixes can be a useful compromise in situations where high quality non-compacted soils cannot be used, but will not produce the same results in an equal volume of quality soil.

Structural soils may increase tree anchorage. Trees were more stable in structural soils than traditional tree pits due to greater root length in gravel-based skeletal soil (Bartens et al. 2010). This is supported by a computer model in which a 20% soil to 80% granite chip mix was optimum for withstanding wind forces required to uproot trees (Rahardjo et al. 2009).

Suspended Pavement

If the pavement is suspended above the soil, the soil does not have to be compacted to support it. Suspended pavements range from elaborate designs constructed on-site to simpler and smaller precast concrete structures. Trees grew better in non-compacted soils under suspended pavement than in compacted soil or two structural soil types (Smiley et al. 2006). The study design did not include non-compacted soil without pavement over it, though experience has shown that trees will grow even better in open soil.

Root Paths

Root paths are narrow trenches installed in a compacted subgrade under pavement to provide a path for roots to grow from restricted planting pits to open spaces on the other side of the pavement. Commercially available strip-drain material is usually installed in the trench and then backfilled with loam soil (Costello and Jones 2003; Urban 2008). It could take several years for roots to grow through the root path and access the soil beyond. There is not yet any research to show that roots are able to effectively take advantage of the paths to access the soil beyond the pavement and improve tree growth and longevity, or that if roots do utilize the paths that they will not lift the pavement.

Soil conditions suitable for root growth under pavements also provide some level of stormwater storage (Day and Dickinson 2008). If significant, this could be additional justification for the higher cost of the expanded root space.

ENHANCING ROOT DEVELOPMENT

Irrigation

Trees are not irrigated in their natural environment. Healthy, established urban trees with adequate root space of quality soil are not typically dependent on irrigation if they are adapted to the climate in which they are growing. Little research is available on irrigation needs of established urban trees. A greenhouse study of ponderosa pine (*Pinus ponderosa*) showed that when water stress occurred during active root growth, the root:shoot ratio was reduced. When water stress occurred during active shoot growth, the root:shoot ratio was increased (McMillin and Wagner 1985; Silva et al. 2012).

Transpiration rates and pan evaporation are strongly correlated for woody species. Transpiration of larger trees is approximately 20% of pan evaporation (Knox 1989; Lindsey and Bassuk 1991). Because of more direct sunlight on the south side of the tree there may be greater water stress on the south side of the tree (Watson and Himelick 1982b; von der Heide-Spravka and Watson 1990). Increased irrigation may be appropriate on the south side of larger trees to compensate. Trickle irrigation can concentrate root development within the wet zones near the emitters (Levin et al. 1979; Mitchell and Chalmers 1983; Fernandez et al. 1991; Watson et al. 2006; Sokalska et al. 2009). Less frequent irrigation with the same amount of water can result in a wider distribution of roots (Levin et al. 1979).

In the summer, soils moist from irrigation and drainage changes can be a major cause of oak (*Quercus*) mortality in Mediterranean climates (Costello et al. 2011). The moisture and warm soil temperatures create conditions favorable to the development of root and crown rot diseases (Swiecki 1990).

Controlled studies of irrigation needs of large trees subject to root severing and loss are difficult to conduct, but studies on irrigation of transplanted trees with substantial root loss can provide information. Newly planted trees have reduced growth if subjected to water stress after transplanting (Haase and Rose 1993). Applying excessive irrigation may reduce root growth and increase the time needed for the tree to develop enough of a root system to survive without irrigation (Gilman et al. 2009). Proper irrigation can reduce secondary stress-related problems, such as bark cracks, sunscald, and injury from borers (Roppolo and Miller 2001).

Fertilization

Total tree root system development is greater when soil nutrients are low (Kodrik and Kodrik 2002). Fertilization may not stimulate root growth unless low levels are already limiting root growth (Philipson and Coutts 1977). An increase in soil fertility is commonly associated with a reduction in the root:shoot ratio; that is, shoot growth increases more than root growth (Ingestad 1960; Philipson and Coutts 1977; Coutts and Philipson 1980; Nambiar 1980; Yeager and Wright 1981; Gleason et al. 1990; Warren 1993; Lloret et al. 1999; Jose et al. 2003; Qu et al. 2003; Rytter et al. 2003).

Fertility can alter the distribution of roots. Fine roots will grow preferentially in pockets of nitrogen rich soil (Wahlenberg 1929), by stimulating the growth of lateral roots (May et al. 1964; Hackett 1972; Eissenstat and Caldwell 1988; Witt 1997). Root growth may be increased even more when nitrogen availability is low outside the pocket (Krasowski et al. 1999). Application of nitrogen to a part of the root system has a strictly localized effect and does not increase overall root growth or alter the shoot:root ratio (Smith 1965; Drew et al. 1973; Drew and Saker 1975; Coutts and Philipson 1976; Carlson 1981; Carlson and Presig 1981; Friend et al. 1990; Sheriff and Nambiar 1995). Enhanced growth of one part of the root system can reduce growth in the other (Weller 1966; Phillipson and Coutts 1977). Severe soil compaction reduced nitrogen fertilizer uptake and was presumably related to the reduced uptake by a smaller root system (Jordan et al. 2003).

Fertilization may be necessary to maintain appropriate vigor and growth rates of urban trees if natural nutrient cycling is interrupted through the removal of fallen leaves and branches. In an Eastern deciduous hardwood forest, nitrogen in fallen litter was measured at 0.27–0.46 kg N/100 m^2/yr (Wells et al. 1972; Larcher 1975). Arboricultural best management practices (Smiley et al. 2007; ANSI 2011) recommend 0.96–1.44 kg N/100 m^2, but allow up to 2.88 kg N/100m^2. These rates far exceed nutrients lost through litter removal and may not be appropriate for slower growing mature trees. Lawn fertilization alone may more than replace nutrients lost by removal of litter (Osmond and Hardy 2004).

Root Stimulants

Paclobutrazol, uniconazole, and flurprimidol are gibberellin-inhibiting growth regulators used primarily to reduce shoot growth of trees, but can also increase root growth under certain circumstances (Numbere et al. 1992). Paclobutrazol may promote root initiation (Davis et al. 1985). Pin oak (*Quercus palustris*) and white oak (*Quercus alba*) fine-root densities were increased significantly throughout the root system by a basal soil drench of paclobutrazol. The treatment may be effective in stabilizing slowly declining trees with insufficient fine-root development (Watson 1996; Watson and Himelick 2004). Fine-root density was not affected by paclobutrazol treatment in a high quality soil environment from long-term mulched application where root density may have been high initially, limiting the ability of paclobutrazol to increase them further (Watson 2006). Species may differ in their response to paclobutrazol. Growth of green ash (*Fraxinus pennsylvanica*) roots was unaffected by paclobutrazol treatment (Watson 2004).

The ability of paclobutrazol to increase root growth may depend on root–leaf area ratio. Paclobutrazol applied at planting doubled root growth on black maple (*Acer nigrum*) in the first season before crown growth was reduced by the paclobutrazol treatment, but not the second when crown growth was greatly reduced (Watson 2004). The large reduction in top growth may have been responsible for the lack of root stimulation in the second year. Gilman (2004) also reported that paclobutrazol had no effect on root growth of transplanted live oaks (*Quercus virginiana*) at a rate that reduced top growth. Root pruning can enhance the growth regulation effects of paclobutrazol treatment and slow root growth (Martinez-Trinidad et al. 2011).

Soil applications of sugar solutions have been tested to increase root growth. Root growth is often but not always increased and may depend on tree species, kinds of sugars, and application rates included in the trials (Percival 2004; Percival et al. 2004; Percival and Fraser 2005; Percival and Barnes 2007; Martinez-Trinidad et al. 2009). Measurable increases in tree vitality are uncommon, even on small experimental plants.

There is extensive published research from a broad spectrum of plant sciences that can be applied to the prevention and mitigation of human impacts on urban tree root systems. The majority of literature available on structural soils, tree root architecture, root locating methods, and root defects has been produced in the last 25 years. At the same time, advances have been made in understanding topics such as infrastructure conflicts and fertilization practices, but these advances are still not fully understood. Arboricultural science is young and growing. There is hardly a topic that would not benefit from extensive additional research. The wide variety of species and environmental circumstances in urban landscapes makes it especially challenging.

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Zusammenfassung. Das Wurzelsystem von nahezu allen Bäumen in bebauten Bereichen ist den Einflüssen von menschlichen Aktivitäten ausgesetzt, welche die Baumgesundheit beeinflussen und die Langlebigkeit reduzieren. Diese Einflüsse sind von der Frühphase der Baumschulentwicklung bis durch das ganze Leben der Bäume präsent. Durch Baumaßnahmen oder Wurzelverlust reduzierte Wurzelsysteme können die Stabilität beeinflussen und den Stress vergrößern. Natürliche Infektionen von Wurzeln bei Straßenbäumen durch Abtrennen führten nachweislich nicht zu extensiver Fäulnis. Wurzeln geraten wegen ihrer Nähe zur Infrastruktur in Konflikt mit der urbanen Umgebung. Strategien zur Bereitstellung von Wurzelraum unter den Pflasterflächen und zur Reduzierung von angehobenen Pflasterflächen wurden entwickelt, aber die Strategien zum Schutz von Fundament- und Abwasserrohrschäden sind begrenzt auf wachsende Separation oder verbesserte Konstruktion.

Resumen. Los sistemas de raíces de casi todos los árboles en el entorno construido están sujetos a los impactos de las actividades humanas que pueden afectar su salud y reducir su longevidad. Estas influencias están presentes desde las primeras etapas de desarrollo en viveros y luego durante toda la vida del árbol. Sistemas de raíces reducidos, pérdida o constricción de las mismas pueden disminuir la estabilidad del árbol y aumentar el estrés. La infección natural de las raíces de los árboles urbanos después de su ruptura no se ha demostrado que conduzca a un extensivo decaimiento. Las raíces a menudo entran en conflicto con la infraestructura en las zonas urbanas debido a la proximidad. Se han desarrollado alternativas para proporcionar espacio para las raíces bajo las aceras y reducir la aglomeración, pero las estrategias para la prevención de daños por pavimentación y tubería de alcantarillado se limitan a aumentar la separación o la mejora de la construcción.