Can Urban Tree Roots Improve Infiltration through Compacted Subsoils for Stormwater Management?

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Global land use patterns and increasing pressures on water resources demand creative urban stormwater management. Strategies encouraging infiltration can enhance groundwater recharge and water quality. Urban subsoils are often relatively impermeable, and the construction of many stormwater detention best management practices (D-BMPs) exacerbates this condition. Root paths can act as conduits for water, but this function has not been demonstrated for stormwater BMPs where standing water and dense subsoils create a unique environment. We examined whether tree roots can penetrate compacted subsoils and increase infiltration rates in the context of a novel infiltration BMP (I-BMP). Black oak (*Quercus velutina* Lam.) and red maple (*Acer rubrum* L.) trees, and an unplanted control, were installed in cylindrical planting sleeves surrounded by clay loam soil at two compaction levels (bulk density = 1.3 or 1.6 g cm^{-3}) in irrigated containers. Roots of both species penetrated the more compacted soil, increasing infiltration rates by an average of 153%. Similarly, green ash (*Fraxinus pennsylvanica* Marsh.) trees were grown in CUSoil (Amereq Corp., New York) separated from compacted clay loam subsoil (1.6 g cm^{-3}) by a geotextile. A drain hole at mid depth in the CUSoil layer mimicked the overflow drain in a stormwater I-BMP thus allowing water to pool above the subsoil. Roots penetrated the geotextile and subsoil and increased average infiltration rate 27-fold compared to unplanted controls. Although high water tables may limit tree rooting depth, some species may be effective tools for increasing water infiltration and enhancing groundwater recharge in this and other I-BMPs (e.g., raingardens and bioswales).

Innovation in urban runoff management is essential to minimize the deleterious environmental effects of global land use changes, especially increased urbanization and population growth (Dwyer et al., 2000; Velarde et al., 2004; Foley et al., 2005; NRCS, 2007). Sensitive watersheds are often heavily urbanized because human settlements frequently originated around water sources and navigable waterways. The Chesapeake Bay watershed in the eastern United States, for example, experienced a 61% increase in developed land from 1990 to 2000 (Jantz et al., 2005). This land conversion increases urban runoff and its associated problems including destroyed habitat, unsafe drinking water, fish kills, beach closures (USEPA, 2005), greatly reduced groundwater recharge, and reduced stream baseflow during dry periods (Schoonover et al., 2006). Repercussions of this altered urban stream hydrology include channel incision and widening, increased suspended sediment concentrations, downstream sedimentation, and increased flooding. Addressing these water quality and supply issues in a sustainable and safe manner becomes more urgent with each passing year.

A new approach to stormwater management in highly built settings detains stormwater under pavement in subgrade reservoirs created by gravel beds, where it is allowed to infiltrate. This double function (pavement subgrade and stormwater management facility [SWMF]) results in efficient use of space and allows water infiltration over a large area. This practice has the potential to more closely mimic natural hydrology than traditional stormwater practices by allowing distributed infiltration on site, rather than concentrating runoff in detention facilities. This distributed management relies on the complex interactions within the rhizosphere to enhance nutrient removal and improve water quality (Hogan and Walbridge, 2007). We are evaluating a novel practice that combines the features of a distributed SWMF with engineered, load-bearing tree substrates (*structural soils*) and large canopy trees. The inclusion of trees directly into a SWMF has

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Abbreviations: BMP, best management practice; D-BMP, detention best management practice; I-BMP, infiltration best management practice; SWMF, stormwater management facility.

many complementary benefits such as canopy interception of rainfall and delivery of water to the soil via trunkflow.

Of interest in such a system is the potential for tree roots to enhance infiltration rates. A SWMF consisting of an underpavement structural soil reservoir (that simultaneously provides additional rooting volume for shade trees) would be effective for recharging groundwater if retained water infiltrated the subsoil below. However, urban soils are heterogeneous and often compacted; thus water infiltration may be severely impeded (Day and Bassuk, 1994; Gregory et al., 2006). It would therefore be desirable in the novel SWMF described above if developing tree roots grew through the structural soil bed and into the local subsoil and thus enhanced water infiltration. In addition, if tree roots were effective at increasing infiltration in this system, they could become a useful tool for a wide variety of I-BMPs that incorporate plants, such as bioretention areas and raingardens. Our objective is to evaluate the potential of trees to play this role in innovative stormwater I-BMPs.

Trees and Stormwater Management

In many rural and forested environments rainwater and snowmelt are retained in forests, wetlands, and grasslands and then slowly infiltrate into the ground. In contrast, nonporous urban structures such as buildings, roads, and parking lots prevent infiltration and even unpaved soil in urbanized areas can have much reduced infiltration rates compared to undeveloped land (Gregory et al., 2006). Urban forests are widely recognized as an effective means of handling stormwater. They intercept rainfall and temporarily store rainwater on the canopy surface (Xiao and McPherson, 2003). Trees also direct precipitation into the ground through trunk flow (Johnson and Lehmann, 2006) and take up pollutants (Szabo et al., 2001) and stormwater through their roots. Individual tree canopies can intercept as much as 79% of a 20-mm, 24-h rainfall under optimum, full-leaf conditions (Xiao and McPherson, 2003). However, canopy cover is greatly limited by urban soil conditions (e.g., compaction, reduced rooting volume, elevated soil pH) and small canopy trees are much less effective at intercepting rainfall.

Likewise, limited land area restricts both conventional and vegetation-based SWMF construction options in urban areas. Current vegetation-based options include raingardens and bioswales. Although these tend to be more distributed than conventional systems (e.g., individual raingardens collect water from a small, nearby drainage area), water is still concentrated into a small subsection of the drainage area. A system using trees and structural soils under pavement as an I-BMP may effectively facilitate the use of a fully distributed stormwater management approach that allows the mitigating potential of trees and soils to function in confined, normally impervious, settings. In such a design, the structural soil subgrade reservoir would be 60 cm or more deep and would be compacted to required engineering specifications. The soil below the structural soil section thus does not require the level of compaction normally specified under pavement for typical streets and parking areas, and wheel loads are instead spread through the compacted structural soil section. Nonetheless, due to trafficking and the inherent density of subsoils or previous fill, these subsoils are typically compacted to the extent that root growth is restricted. The high porosity of structural soils after compaction (30–35%) means that structural soil reservoirs under pavement can serve simultaneously to store stormwater and allow greater tree root extension. Ample rooting area allows trees to form larger canopies in urban settings (Lindsey and Bassuk, 1991; Grabosky and Gilman, 2004), which in turn reduce rain throughfall to the ground.

Structural Soils

Structural soils consist of a stone and a mineral soil component that together form a highly porous (30–35%) matrix with a high load-bearing capacity that still permits tree root growth. CUSoil is a gravel-soil mix developed at Cornell University, Ithaca, NY, in the mid-1990s (Grabosky and Bassuk, 1998) to address one of the central issues limiting tree growth in urban areas: insufficient soil volumes for tree root development. The primary objective of the structural soil research was to create a substrate that would both allow adequate tree root growth *and* support pavement for sidewalks, streets, and parking lots (Grabosky and Bassuk, 1995). Structural soils are appropriately used as the structural section under pavement that surrounds tree planting areas, where roots would not normally be able to penetrate—not as a substitute for mineral soil in planting pits. Thus the use of these soils can provide additional rooting volume for trees beyond what would normally be accessible. It is important to note that structural soils are typically only 20% mineral soil, so large volumes are needed to provide sufficient resources to trees (Loh et al., 2003). Other structural soil mixes have now been developed, such as a mixture containing Carolina Stalite (a heat expanded slate, Carolina Stalite Company, Salisbury, NC) as the stone component (Costello and Jones, 2003). With the expanded rooting volume provided by placing structural soil under pavement, trees have the potential to develop full canopies even in heavily paved settings and thus to intercept rainfall more effectively.

Preferential Flow along Root Channels

Water can flow preferentially along tree roots in forested and agroforestry settings allowing roots to strongly influence water movement through soils (Johnson and Lehmann, 2006). Bramley et al. (2003) found infiltration through flooded impoundments containing trees was 2 to 17 times faster than in impoundments without trees. Tracer dyes indicated this increase was primarily mediated by preferential flow (water flow along macropores that bypasses the bulk soil). However, these studies focused on soils with long-established woody vegetation, which, through processes such as root turnover and litter accumulation and decomposition, affects soil physical and biological properties. Plant roots have been proposed as biological drills or tillers, but have been only marginally successful, presumably because of inability to penetrate compacted soils and small root diameters that have little impact on permeability (Cresswell and Kirkegaard, 1995). In a study using shelter belts of *Acacia* spp., *Eucalyptus* spp., and *Casurina* spp., Yunusa et al. (2002) found the roots of woody plants increased macroporosity, hydraulic conductivity, and preferential flow, but these effects were not evident until after 6 yr when the woody plants had been removed and the roots decayed.

Root Penetration of Urban Subsoils

Urban subsoils are typically heavily compacted by trafficking during building, road, and pavement construction. In addition, the infrastructure of built environments often restricts traditional techniques (such as deep tillage) for enhancing soil permeability. Therefore, the possibility of roots penetrating through impermeable layers into more permeable zones could greatly aid overall stormwater infiltration for a variety of I-BMPs. Although high soil strength can inhibit root penetration (Barley, 1963), bottomland species may be better adapted to penetrating high density soils when the soil water content is high and soil strength consequently low (Day et al., 2000). Subsoils immediately below a stormwater reservoir are likely to remain wet for extended periods and may provide a unique opportunity to exploit the potential of roots for increasing infiltration.

Objectives

We conducted two separate experiments (a one-growing-season greenhouse study, and a 2-yr field study) to examine the immediate effect of living trees on the hydraulic conductivity of an urban subsoil (devoid of preexisting vegetation). These experiments are posed in the context of the I-BMP using structural soils described above; however, results may be applicable to a large number of stormwater applications. These studies address the following questions:

1. Will tree roots grow into compacted subsoil similar to what would be encountered below a stormwater BMP?
2. Will tree root development increase the infiltration rate of compacted soil?
3. Does a coarsely-rooted species such as black oak have a greater effect than a finely rooted species such as red maple?
4. Will tree roots penetrate a woven geotextile into a compacted-soil zone?

Experimental Methods

Greenhouse Study (Experiment 1)

Experiment 1 was conducted at the campus greenhouses at Virginia Tech in Blacksburg, VA. Bare-root red maple and black oak trees produced by Heritage Seedling, Inc. (Salem, OR) were used in addition to a no-tree control. In February 2006, 2-yr-old seedlings of each species were planted in a cylindrical reservoir of pine bark nursery substrate (2.2 L) in the center of 23.7-L containers, with compacted subsoil on all sides and below the pine bark (Fig. 1). This subsoil was from the B horizon of a Groseclose (fine, mixed, semiactive, mesic Typic Hapludults) series from Montgomery County, Virginia (15.4% sand, 35.3% silt, and 49.4% clay). Soil was compacted to two different levels (see below), using a replicable compaction protocol with a Proctor hammer. No-tree controls were constructed in the same way for each compaction level. All containers (with trees and without) were irrigated thoroughly by hand approximately twice a week or more often when trees showed any visual indication of drought stress. Thirty containers were placed in a completely randomized design with five replications of three tree treatments (two species + no-tree) at two compaction levels ($30 = 5 \times 3 \times 2$).

Compaction Treatments

Nursery containers (volume = 23.7 L, height = 30 cm, diameter at top = 34 cm) were evenly filled to either a 14-cm depth (compaction level 1) or a 16-cm depth (compaction level 2) with soil. A tightly fitting wooden board fashioned from 2-cm thick plywood was laid on top and struck 10 times (compaction level 1) or 20 times (compaction level 2) by dropping a 4.54-kg Proctor hammer from a 60-cm height. The board was removed and a 15-cm diam. poly-vinyl chloride (PVC) pipe was placed in the center and surrounded by an additional layer of clay loam (14 cm for level 1; 16 cm for level 2). A wooden ring, also completely covering the now ring-shaped soil surface, was then placed on top of the soil and struck 10 times (level 1) or 20 times (level 2) from a 60-cm height by the Proctor drop-hammer. The PVC pipe was removed and a 15-cm diam. PVC ring, 10 cm in height, was placed 5 cm below the soil surface to serve as a collar for the infiltration measurements, before filling the center with pine bark and planting the tree (no tree for the control). This pre-established protocol produced the same finished height for all treatments and resulted in soil dry bulk densities that (measured via undisturbed core samples) averaged 1.31 g cm^{-3} (12.8 kN m^{-3} unit weight) for compaction level 1 (1.34 g cm^{-3} side and 1.23 g cm^{-3} bottom) and 1.59 g cm^{-3} (15.5 kN m^{-3} unit weight) for compaction level 2 (1.63 g cm^{-3} side and 1.50 g cm^{-3} bottom). Since the compaction force was distributed over a greater surface area for the bottom layer than for the side layer, it may be that more compaction effort was delivered to the sides than the bottom, thus explaining the higher side bulk density. These compaction levels are consistent with levels restrictive of root growth for soils of similar texture (Zisa et al., 1980; Daddow and Warrington, 1983; Day et al., 2000) and commonly found in urban areas. Daddow and Warrington (1983) calculated a growth-limiting dry bulk density (tree root growth essentially halts) for clay loam soils as 1.45 to 1.55 g cm^{-3} at field capacity (gravitational water drained away).

Infiltration Measurements

Because saturated flow through the soil profile will provide a more consistent and repeatable measurement of conductivity, containers were flooded for 2 d to bring the soil to saturation before measuring the infiltration rate. To ensure complete saturation, we filled portable children's swimming pools with water to within a few centimeters of the soil surface for 2 d and allowed the water to reach the soil surface through capillary action. Pools were drained immediately before measurements. Infiltration rate was measured on six dates: 15 May, 15 June, 9 and 20 July, 3 Aug., and 6 Sept. 2006. After complete saturation of the soil/pine bark system, 1 L of water was poured into the PVC collar and the time necessary for the water to infiltrate (no water being visible on the pine bark surface) was measured. Containers had numerous drainage holes at the bottom, permitting water to drain freely during measurements.

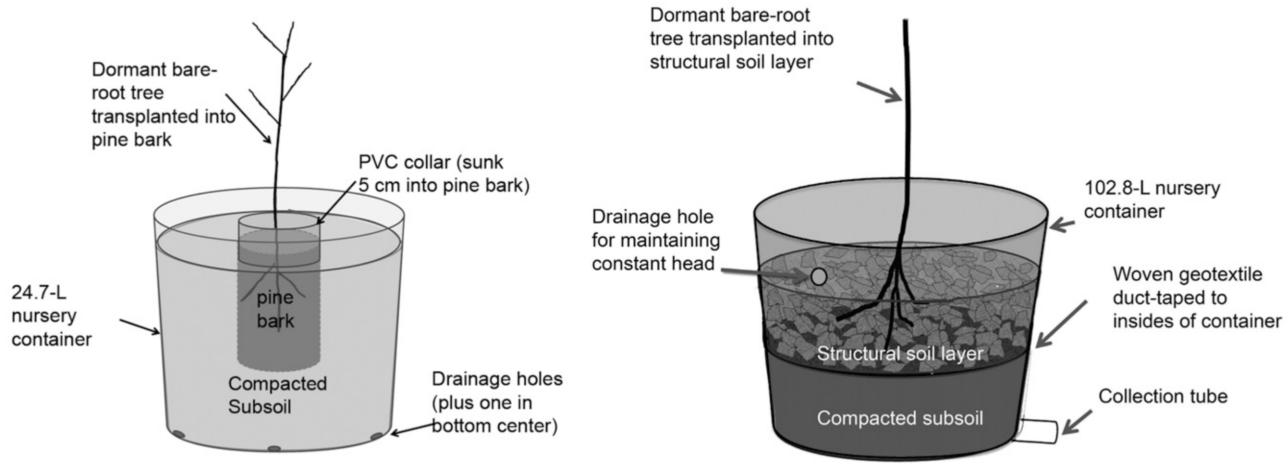

Fig. 1. Schematic of container setup for experiments (not to scale). Left figure shows Exp. 1 (greenhouse study) and right figure shows Exp. 2 (structural soil profile study). Structural soil is CUSoil and is separated from compacted subsoil below by a woven geotextile.

This test was repeated and the two subsamples averaged. Because the system was saturated, this measurement provided a relative measurement of saturated hydraulic conductivity of the most restrictive part of the system (the subsoil in this case).

Root Growth

In September 2006, root presence vertically and horizontally within the compacted soil was determined by cutting two 2-cm slices off the soil from the bottom and sides and counting the cut root ends (Fig. 2). Since the containers tapered toward the bottom, surface areas for cuts starting at the bottom were 707 and 855 cm^2, respectively. Container bottoms were removed by cutting around the circumference and then through the soil and roots with a hacksaw. A brush was used to clear loose soil and make cut root ends visible for counting. Because of the great number of root tips in most containers, the roots on the bottom slices were counted on two pie-shaped samples totaling 25% of the surface area and total root ends calculated (Fig. 2, left). The procedure was repeated for the second slice. Pots were then completely removed and a 2-cm slice was cut from the side, the soil brushed, and roots counted. The counting surface area was 130-cm^2 centered horizontally on the soil face to capture roots emerging from the pine bark (Fig. 2, right). A second 2-cm slice was cut from the same side and roots counted for the same area. Counts were calculated on a per-unit-surface-area basis.

Structural Soil Profile Study (Experiment 2)

Nursery containers (volume = 102.8 L, height = 46 cm, diameter at top = 60 cm) without drainage holes, were treated with SpinOut, a copper hydroxide paint (Griffin LLC, Valdosta, GA) to keep roots in the interior of the container. A drainage outlet at the base was constructed using a 10-cm length of 3.75-cm diam. PVC pipe. Fiberglass mesh screening was placed inside the container over the drain to prevent soil loss and a weatherproof sealant applied to prevent leakage around the joint. A 6-cm diam. hole was drilled just below the rim in the side of each pot to make it possible to keep water at a constant level to facilitate hydraulic conductivity measurements.

Profile Construction and Compaction

Soil profiles were assembled in the containers to simulate a stormwater reservoir of structural soil separated from compacted subsoil by a geotextile. The subsoil was constructed by compacting a clay loam (25.9% sand, 36.9% silt, and 37.2% clay) in three lifts. For each lift we placed 22.5 kg of soil (18.28 kg dry wt.) in the container, placed a fitted wooden board over the soil and compacted it with 12 blows from a 4.5- kg Proctor hammer dropped from a height of 60 cm. At the time of construction, the subsoil dry bulk density was calculated as 1.63 g cm^{-3} (16.0 kN m^{-3} unit weight) via one undisturbed core sample of 92 cm^3 volume, dried at 105°C to a constant weight. At harvest, 2 yr later, nine additional samples (three from each of three no-tree pots) were taken using the excavation method (Blake and Hartge, 1986) and an average dry bulk density of 1.51 g cm^{-3} (14.8 kN m^{-3} unit weight) was determined. A circular piece of woven geotextile (250 g m^{-2} mass per unit area) was placed over the compacted subsoil and sealed with duct tape to the insides of the container. Containers were then filled to the top with CUSoil (Grabosky and Bassuk, 1998), a structural soil. The structural soil was mixed in a small cement mixer at a 78:22 dry weight ratio of limestone quarry stone and the soil described above. Gelscape, a potassium propenoate-propenamide copolymer hydrogel (Amereq Corp., New York, NY) was added at a rate of 0.03% (by weight) to bind the soil to the stone and prevent segregation. The stone consisted of Virginia Department of Transportation size number 357 open-graded coarse aggregate (1.5–4.0 cm diam.).

Structural Soil Section

In May 2005, 10 of these pots were prepared as described above and bare root *Fraxinus pennsylvanica* Marsh. (green ash) trees (1–2 cm trunk diameter at 15 cm above soil line) were planted into five randomly selected pots as structural soil was installed. Structural soil was tamped for all pots (tree and no-tree) using two semi-circular boards that closely fit the exposed surface and striking each board 16 times with

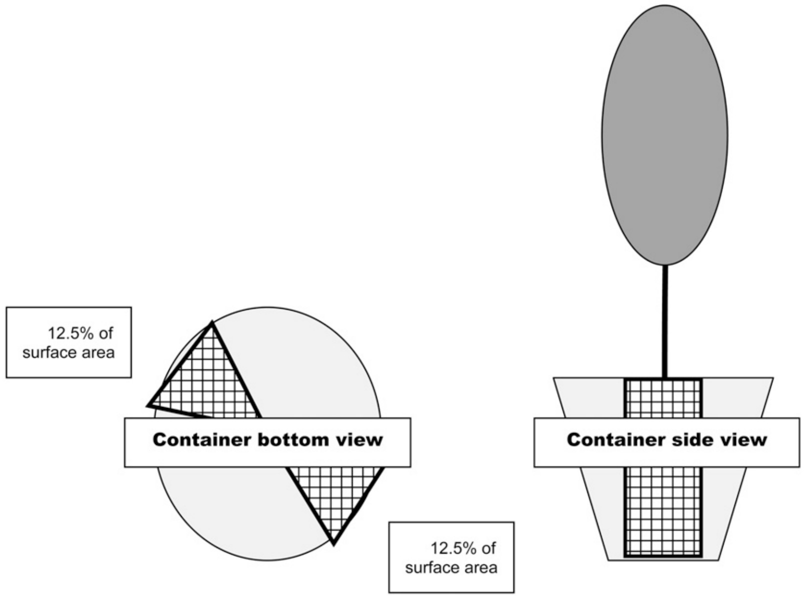

Fig. 2. Schematic of root count sampling area for Exp. 1 (not to scale). Grids represent sample area and wire mesh used to facilitate counting of root ends. Left figure shows bottom of pot and two wedge-shaped sampling areas comprising 25% of surface area. Right figure shows sample area from side slices.

the Proctor hammer (60-cm drop). All pots (including no-tree pots) were irrigated with micro spray emitters so trees could establish. A drainage hole was made in the side of each pot in the middle of the structural soil zone to prevent water from ponding for long periods, serving the same function as an overflow pipe in a field installation. Pots were placed on elevated platforms at the Urban Horticulture Center field research area in Blacksburg, VA to allow access to the bottom drains for water collection.

Hydraulic Conductivity Measurements

Trees were grown for 2 yr before saturated hydraulic conductivity (K_{sat}) was measured using a constant head technique (described below) in May 2007. Earlier overflow drain holes were sealed and pots and subsoils were saturated via repeated irrigation and rainfall for 1 wk in advance of measurements. In addition to saturating the system, this was intended to reduce or eliminate boundary flow down the sides of the container by settling soil completely against the container sides. Pots were not moved after this point. Some no-tree pots had no water draining from outlet tubes, indicating this methodology was successful at preventing short-circuiting. Pots were filled until excess water began to drain out of the 6-cm hole just below the rim and just above the surface of the structural soil. This constant head of water was maintained with irrigation micro spray emitters during measurements. Water was collected from the outlet pipes of each container for at least 60 s and the volume measured. Collection was repeated twice and subsamples averaged. We assumed no loss of hydraulic head in the highly permeable structural soil layer. The coarse weave of the geotextile used allowed water to move freely and there was no indication that the geotextile was clogged at any time, including during harvest at the end of the experiment. Therefore, when calculating the harmonic mean of K_{sat} for this vertically layered system, the terms for the structural soil and geotextile layers were insignificant as compared to the term for the compacted subsoil, due to the relatively high individual values of K_{sat} for these layers. The overall K_{sat} was therefore calculated as $K_{sat} = (L \times Q)/(\Delta H \times A)$, where ΔH = the height of upper drain hole from the bottom of the pot, L = the height of the subsoil profile, Q = water volume flow rate, and A = mean cross-sectional area of the subsoil. Means were compared using the nonparametric Wilcoxon (Rank Sums) Two-sample Test in SAS (two-sided t approximation) (SAS Institute, 2003).

Root Measurements

Trees were harvested in May 2007 and subsoil washed from below the geotextile. Roots larger than 2 mm in diameter at the point of emergence from the geotextile were counted and their diameters measured with microcalipers. In addition, we recorded the depth of the deepest root and whether any roots traveled down the container sides. All roots that penetrated the subsoil were severed at the geotextile and washed free of soil in a no. 10 soil sieve (2-mm mesh). These roots were dried to a constant weight at 70°C and weighed.

Statistical Analyses: Experiments 1 and 2

Unless otherwise described, all experimental data were analyzed by analysis of variance with the GLM procedure of SAS (SAS Institute, 2003). Root counts in Exp. 1 were transformed by taking the square root before analysis, since distribution of the count data was Poisson (not normally distributed), and the means and variance were not independent (Sokal and Rohlf, 1994). Regression analysis between hydraulic conductivity and root growth variables was performed in SigmaPlot (Systat Software, 2004).

Table 1. Effect of red maple and black oak trees on infiltration rate through soil compacted at two levels: dry density Level 1 = 1.31 g cm^{-3} (12.8 kN m^{-3} unit wt.); Level 2 = 1.59 g cm^{-3} (15.5 kN m^{-3} unit wt.) (Exp. 1).

	Infiltration rate						
Compaction level	15 May†	15 June	9 July	20 July	3 Aug.	6 Sept.	Percent change‡
	mL s^{-1}						%
Compaction level 1							
Red maple	19.27 (2.74)	14.99 (3.24)	7.17 (2.06)	13.83 (4.00)	6.63 (2.65)	9.71 (2.94)	−49.6
Black oak	25.32 (3.78)	23.92 (2.86)	6.51 (3.16)	17.89 (3.04)	14.49 (3.68)	11.85 (2.44)	−53.1
No tree	10.59 (1.48)	5.82 (0.80)	2.02 (0.44)	5.34 (0.73)	3.75 (0.89)	4.18 (0.69)	−60.5
Compaction level 2							
Red maple	7.49 (1.08)	7.60 (0.90)	4.72 (1.28)	8.00 (1.02)	6.70 (0.72)	4.10 (1.26)	−45.2
Black oak	9.86 (1.23)	9.13 (1.96)	6.39 (2.16)	8.13 (0.94)	7.30 (1.51)	7.40 (1.56)	−24.9
No tree	6.31 (0.46)	4.44 (0.16)	2.10 (0.26)	5.77 (0.92)	3.94 (0.59)	1.06 (0.31)	−83.2
	Contrasts $P > t$§						
Compaction level 1							
Red maple vs. no tree	0.032	0.001	0.001	0.001	0.061	0.435	
Black oak vs. no tree	0.007	0.001	0.002	0.001	0.003	0.376	
Red maple vs. black oak	0.516	0.298	0.887	0.567	0.179	0.915	
Compaction level 2							
Red maple vs. no tree	0.195	0.001	0.012	0.101	0.090	0.001	
Black oak vs. no tree	0.006	0.001	0.003	0.089	0.060	0.001	
Red maple vs. black oak	0.100	0.355	0.575	0.945	0.837	0.554	

† Trees planted on 10 Feb, 2006. Numbers are mean of five replications (two subsamples per replication) with standard error of the mean in parentheses. All measurements were made in 2006.

‡ Calculated as total change from 15 May to 6 September.

§ Contrast *P* values were calculated by PDIFF within the GLM procedure of SAS.

Results

Greenhouse Study (Experiment 1)

Infiltration

There was strong evidence that the presence of black oak and red maple trees increased the infiltration rate through the subsoil relative to containers that did not have trees (Table 1). The increase in drainage rate was evident at the first infiltration test date (within 12 wk) except for red maple at compaction level 2 (Table 1). This indicates that woody roots can increase infiltration relatively quickly before there is opportunity for very large diameter roots to form and when root turnover is likely minimal. Although individual roots of young trees may survive only a few weeks (Black et al., 1998), the actively establishing root system likely did not have sufficient time to produce roots and have them die and decompose before infiltration tests were started, and we did not observe dead roots during counting. Therefore, in contrast to results reported in field experiments by Yunusa et al. (2002), it seems probable that water travelled in the root channels along existing live roots.

Overall, combining all measurement dates, compaction levels, and species, trees increased infiltration rate by an average of 63% when compared to the no-tree containers. In the severely compacted treatment, trees increased infiltration rate by an average of 153%. As expected, the infiltration rate for both species and the no-tree control was greater for compaction level 1 than compaction level 2 over the course of the study since the small pore sizes and more tortuous paths of compacted soil generally restrict K_{sat}. Infiltration rate did not increase over time as expected for the containers with trees. However, although they were dormant at planting, trees were apparently well established 3 mo later at the first measurement date and the series of subsequent measurements therefore did not capture the transition time during which the roots grew into the compacted subsoil. Instead, an overall mean decrease in infiltration rate of 53% was observed across all treatment combinations from 15 May to 6 September, presumably as a result of soil settling from repeated irrigation. However, for compaction level 2 the difference between tree and no-tree treatments strengthened over time, indicating that the presence of tree roots helped to maintain infiltration rates (see contrast *P* values in Table 1).

To permit comparison between Exp. 1 and 2 (see below), an approximate K_{sat} was calculated using a modification of Glover's solution for hydraulic conductivity in an augered hole (Amoozegar, 1989). This modification is an asymptotic steady-state flow model and assumes soil extends outwards indefinitely in all directions from the augered hole (i.e., an open field situation), a condition not met in this container experiment. However, because water can move freely through the drainage holes, it is a very close approximation and allows a general comparison of rate between experiments. By this approximation, average K_{sat} was 1.3×10^{-3}, 3.0×10^{-3}, and 3.9×10^{-3} cm s^{-1}, for no-tree, red maple, and black oak, respectively in compaction level 2.

Species Effects on Infiltration

For both compaction levels and for every measurement date except one (9 July, compaction level 1), soils with black oak trees (a species with a coarse root system) drained more rapidly than those with red maple trees (a species with a fibrous root system). However, variability was high and there is a distinct likelihood that this difference was due to factors other than species (see contrast *P* values in Table 1). Although decrease in infiltration rate over the course of the experiment was consis-

Table 2. Number of roots per cm^2 of surface area of exposed subsoil. Roots were counted at the soil face created by slicing soil at 2-cm intervals from the bottom and sides of containers for two tree species, black oak and red maple, that were planted in soil compacted at two levels: dry density of Level 1 = 1.31 g cm^{-3} (12.8 kN m^{-3} unit wt.); Level 2 = 1.59 g cm^{-3} (15.5 kN m^{-3} unit wt.). (Exp. 1).

	Root ends per cm^2 surface area at each location†			
	2 cm from bottom	4 cm from bottom	2 cm from exterior side	4 cm from exterior side
Black oak				
Compaction level 1	1.22 (0.29)	1.10 (0.19)	2.28 (0.49)	2.54 (0.58)
Compaction level 2	1.46 (0.18)	1.03 (0.15)	1.81 (0.46)	2.22 (0.59)
Red maple				
Compaction level 1	1.16 (0.06)	0.37 (0.20)	1.30 (0.60)	2.33 (0.76)
Compaction level 2	0.90 (0.69)	1.31 (1.00)	1.29 (0.42)	1.93 (0.58)
		Contrasts $P > t$‡		
Black oak compaction level 1 vs. 2	0.43	0.87	0.51	0.67
Red maple compaction level 1 vs. 2	0.41	0.50	0.996	0.67

† $n = 5$, numbers in parentheses are the standard error of the mean.

‡ Contrast *P* values calculated by PDIFF within the GLM procedure of SAS. All data were transformed to square roots before statistical analysis. Data presented in tables are not transformed.

tent in compaction level 1, in compaction level 2 the decrease was greatest for no-tree pots (83%), followed by red maple (45%), and black oak (25%) (Table 1). Although we standardized procedures as much as possible (e.g., used the same operator for infiltration tests), high variability is common in soil and root systems and species comparison at each date do not reveal evidence for a species effect (Table 1). Further study may be merited on the influence of species and root architecture.

Root Distribution

Roots of both tree species grew into all layers of the surrounding compacted subsoil. Some containers had a few roots growing a short distance out of the bottom drainage holes during the course of the experiment. There was no evidence that compaction level influenced root distribution in either species (Table 2), indicating that black oak and red maple seedlings are equally capable of penetrating soils of different compaction degrees under the conditions of our experiment. In finer-textured soils, such as those used in this experiment, tree root growth restriction is clearly evident at bulk densities lower than those achieved in the present study (Zisa et al., 1980; Day et al., 2000). The potential of red maple and black oak trees to penetrate compacted soils is demonstrated in the present study, but field soils may be stronger and roots may have other avenues for growth (unlike this study where all root growth beyond the pine bark core was, by necessity, into compacted subsoil). Nonetheless, roots clearly grew throughout the soil profile, showing the potential for tree roots to penetrate compacted soils, especially when saturated for prolonged periods. As soil moisture content increases, as would occur more often in a stormwater BMP than in surrounding soils, soil strength decreases and bottomland tree species can exploit this opportunity for growth (Day et al., 2000).

Structural Soil Profile Study (Experiment 2)

Hydraulic Conductivity

Saturated hydraulic conductivity (K_{sat}) was very low for pots with no trees (Table 3). All pots with trees drained more rapidly than those without trees: trees increased drainage by a factor of 27 (on average), with some draining extremely rapidly (Table 3).

Influences of Root Growth

All containers with trees had roots that grew through the geotextile into the compacted subsoil. Every tree had at least one root that penetrated to the bottom of the container. Green ash is very tolerant of prolonged flooding (Whitlow and Harris, 1979) and therefore may be well adapted to penetrating wet, compacted soils. K_{sat} was weakly related to total cross-sectional root area penetrating the geotextile ($R^2 = 0.31$) and more strongly to the total dry weight of roots below the geotextile (per volume of subsoil) ($R^2 = 0.43$) (Fig. 3). Other factors, such as root architecture, may play a role in influencing K_{sat}. Root mobility appeared somewhat constricted by the geotextile; however, it is impossible to determine whether this restriction is due to the compacted subsoil beneath the geotextile or the geotextile itself. Visually, roots proliferated in the CUSoil layer but were more limited in the compacted subsoil layer. However, we observed that on two trees where geotextile fibers were broken (either by roots or by gravel during the compaction process), as opposed to simply deformed, roots proliferated (Fig. 4). Roots did not grow down the edges of the containers, nor did they circle at the bottom or emerge from drainage holes.

Discussion

These two experiments offer evidence that tree roots can alter the drainage properties of compacted subsoils under certain conditions. Roots grew into compacted soils in all cases,

Table 3. Saturated hydraulic conductivity of and root penetration into a containerized structural soil-geotextile-compacted subsoil profile designed for stormwater infiltration with and without green ash trees. Trees established for 2 yr before measurements (Exp. 2).

	Saturated hydraulic conductivity (K_{sat}) cm s^{-1}†	Average number of roots penetrating into subsoil	Average diameter of roots ≥2 mm at point of emergence from geotextile
Containers with trees	1.31×10^{-3}	6.33	5.28 mm
Containers without trees	4.83×10^{-5}	n/a	n/a
P value‡	0.008	n/a	n/a

† $n = 5$.

‡ *P* value calculated in SAS with the Wilcoxon Rank Sum Test.

although this penetration may require that soils remain moist or wet and that tree species have some tolerance of moist or flooded soils (Day et al., 2000). Both of these conditions were met in these experiments. In the first experiment where trees were planted in pine bark cylinders, trees increased system drainage by an average of 153% in severely compacted soil as compared to unplanted controls. In the second experiment with a structural soil profile, K_{sat} increased by a factor of 27. Possible reasons for this more dramatic increase are that the initial K_{sat} of the structural soil system was far lower, possibly because the subsoil was somewhat more compacted. K_{sat} in no-tree pots was not as low in the greenhouse experimental setup (estimated at 1.30×10^{-3} cm s^{-1}) as in the structural soil profile experimental setup (4.83×10^{-5} cm s^{-1}). In addition, the trees in the structural soil profile experiment were quite a bit larger (average height and trunk diameter at 15 cm above soil line was 1.8 m and 2.4 cm at harvest, respectively) and had grown in situ for 2 yr. Root diameters were correspondingly larger.

Both experiments captured the establishment phase of root growth in transplanted trees. This is the critical phase on which tree survival depends. In addition, because roots can penetrate these compacted subsoils in this early stage of tree development when they do not have access to additional water and nutrient sources, this provides compelling evidence that root penetration and increased infiltration would be possible in other, less restricting environments that might contribute to increased tree vigor. On the other hand, some tree species have root foraging strategies that might reduce penetration of undesirable soils if more nutrient-rich soil volumes were available elsewhere (Mou et al., 1997). In urban stormwater BMPs however, trees are unlikely to have access to such soil resources.

In most stormwater I-BMPs, tree roots would have a much larger penetrable soil volume than in our experiments. In such cases, tree roots would have more opportunity for horizontal growth. The effect of root growth on drainage could also be mitigated by several other factors. High water tables resulting from extremely slow draining systems may restrict downward root growth (Ray and Nicoll, 1998), although this is not always the case with some flood-tolerant species (Rodgers et al., 2003). In addition, our experiments were conducted in containers. Roots were observed to exit the bottoms of the pots in many cases in the first experiment, presumably providing a tunnel from the pine bark reservoir all the way through to the outside air. In the field, roots will terminate within the soil layers and drainage could be impeded if dense layers exist below the portion of subsoil exploited by roots. However, the B3 and C horizons of upland residual soils can be more pervious than the overlying horizons due to presence of unsaturated fractured and/or decomposed parent material. Root growth into B3 and/or C horizons could potentially allow enhanced infiltration. This effect would be expected to increase over time as larger roots die and decompose. Also, although roots penetrated the geotextile used in this experiment, it may still have impeded root growth and development. In addition, all

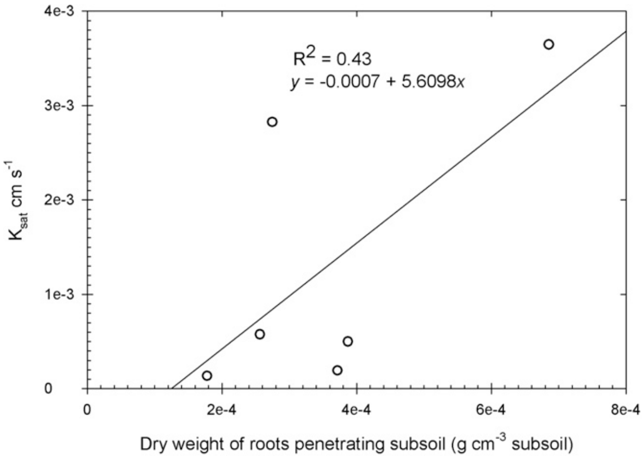

Fig. 3. Effect of root penetration on saturated hydraulic conductivity (K_{sat}) of subsoil in Exp. 2. Dry weight includes all roots of green ash trees crossing a woven geotextile into a compacted soil layer.

geotextiles may not perform equally well. Further study with perforated geotextiles may provide better materials for construction of vegetated I-BMPs.

Urban soils are commonly very disturbed from excavation, hauling soil to or from other locations, soil compaction, and other human modification. Soils used in this container experiment were also disturbed, since they were excavated, transported, filled into the container and compacted. Soil bulk densities were within the expected range for urban soils of this textural class; therefore, the soils in our experiments received

Fig. 4. Root penetration through woven geotextile. Roots of green ash emerge through woven geotextile where compacted subsoil has been washed away. Arrow indicates point of root proliferation where geotextile fiber is ruptured. (Exp. 2).

treatments similar to soils in land under development (and thus present in urbanizing and urbanized land).

We tested three species, all of which resulted in increased infiltration rates compared to controls with no trees. Since the root structure of black oak is rather coarse and those of red maple and green ash fine, roots of a variety of other tree species may have similar effects on the infiltration rate if root penetration can be established.

Soil heterogeneity may lead to an overall high infiltration rate (even if infiltration rate measurements indicate low infiltration), because cracks or other localized rapidly-draining areas in the soil can remove water from a large area (DeBusk, 2008). These experiments demonstrate that tree roots can grow into compacted subsoil and increase infiltration rates. Such localized increases in infiltration rate potentially have wide-ranging effects. We would expect trees that tolerate wet soils and relatively high pH (~8.0) to perform best in the structural soil stormwater BMP described when constructed with limestone-based structural soil. Many bottomland species naturalize in wet areas because they tolerate those conditions better than other species, or because standing water protects them from fire. Many of these trees also perform well in drier conditions and constitute a large proportion of the most common and successful street tree species. Bald cypress [*Taxodium distichum* (L.) L.C. Rich.], for example, can grow in upland and bottomland soils, and therefore submerged or drier soils. Among others, American elm (*Ulmus americana* L.), and London plane [*Platanus* X *acerifolia* (Ait.) Willd.] may also be effective species for this proposed system, as well as in other bioinfiltration stormwater BMPs. The species used in the present studies have varying degrees of tolerance for waterlogged soils. Black oak grows well in very moist soils, but is intolerant of more than a few days of flooding (Whitlow and Harris, 1979). Red maple is tolerant of at least 10 d of submersion with no ill effects, and up to an entire growing season without significant mortality (White, 1973; Whitlow and Harris, 1979). Green ash is tolerant of extended submersion of at least 150 d (Bell and Johnson, 1974). Tolerance for waterlogged soils may also confer some ability to penetrate compacted soils when they are saturated and soil strength is consequently low (Day et al., 2000). Indeed, in this experiment soils were kept saturated before measurement, thus providing extended periods when soil strength was likely reduced and root growth opportunity would be enhanced for species tolerant of these wet conditions. If water were stored in a stormwater BMP in a slowly draining soil, subsoils may be expected to remain saturated and soft. However, if water tables remain continuously high, rooting depth may be restricted, even in flood-tolerant species. Therefore careful species selection and water table control through the BMP drainage system design would maximize possible benefits for a range of I-BMPs, such as structural soil and bioretention cells.

In subsoils with a dominant clay component, such as those used in this experiment, soil strength will decrease with increasing moisture content. Root penetration of compacted subsoils likely relies on this feature, the use of flood-tolerant tree species, and a high moisture content that can result from a BMP design that allows water to be retained (i.e., overflow pipes are not located at the bottom of the BMP). When these conditions are met, vegetation-based I-BMPs, including the introduction of highly distributed stormwater systems such as the structural soil system described, can incorporate trees as an active component of infiltration enhancement.

Conclusions

Roots in all three experiments penetrated compacted subsoils, resulting in increased water infiltration rates through these compacted zones. In the second experiment, roots penetrated a woven geotextile used to separate structural soil and subsoil below, but penetration appeared enhanced where there were tears in the geotextile. Although there was some indication that the coarse-rooted species (black oak) increased infiltration more than the fine-rooted species (red maple), the data presented here could not confirm that this increase was due to species. Overall, our results suggest great potential for trees to increase infiltration rate and potentially the capacity of many types of I-BMPs, allowing such facilities to handle greater water volume and contribute to groundwater recharge.

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