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Transpiration and Root Development of Urban Trees in Structural Soil Stormwater Reservoirs

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Abstract Stormwater management that relies on ecosystem processes, such as tree canopy interception and rhizosphere biology, can be difficult to achieve in built environments because urban land is costly and urban soil inhospitable to vegetation. Yet such systems offer a potentially valuable tool for achieving both sustainable urban forests and stormwater management. We evaluated tree water uptake and root distribution in a novel stormwater mitigation facility that integrates trees directly into detention reservoirs under pavement. The system relies on structural soils: highly porous engineered mixes designed to support tree root growth *and* pavement. To evaluate tree performance under the peculiar conditions of such a stormwater detention reservoir (i.e., periodically inundated), we grew green ash (*Fraxinus pennsylvanica* Marsh.) and swamp white oak (*Quercus bicolor* Willd.) in either CUSoil or a Carolina Stalite-based mix subjected to three simulated below-system infiltration rates for two growing seasons. Infiltration rate affected both transpiration and rooting depth. In a factorial experiment with ash, rooting depth always increased with infiltration rate for Stalite, but this relation was less consistent for CUSoil. Slow-drainage rates reduced transpiration and restricted rooting depth for both species and soils, and trunk growth was restricted for oak, which grew the most in moderate infiltration. Transpiration rates under slow infiltration were 55% (oak) and 70% (ash) of the most rapidly transpiring treatment (moderate for oak and rapid for ash). We conclude this system is feasible and provides another tool to address runoff that integrates the function of urban green spaces with other urban needs.

Keywords Best management practices (BMPs) · Sap flow · Transpiration · Urban forestry · Urban hydrology

Introduction

Increased urbanization results in increased impervious surface area and thus increased stormwater runoff leading to impaired water quality, threatened water supplies, and reduced groundwater recharge (Dittrich and Münch 1999; Jantz and others 2005; Tu and others 2007). Increased runoff can lead to rapid and extreme fluctuations in stream flow, resulting in severe channel erosion and aquatic habitat degradation (Boland and others 1993; Paul and Meyer 2001; Schoonover and others 2006). Urbanization is expected to continue at increasing rates (Velarde and others 2004; NRCS 2007), so pollution, runoff, and decreasing groundwater recharge are of growing concern (Foley and others 2005).

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Urban residents place high value on the most tangible environmental functions of urban forestry such as shade and cooling (Jim and Chen 2006), and society is increasingly relying on trees to fulfill particular functions rather than to simply provide a background level of environmental protection services (Nowak 2006). Urban forest canopies are effective at reducing stormwater runoff due to rainfall storage on leaves until removal by evaporation, and channelization of water down stems and trunks (i.e., trunk flow) into the soil and away from impervious surfaces (Xiao and McPherson 2003; McPherson and others 2005). Increased canopy cover can result in reduced surface runoff in urban areas (Wang and others 2008). To achieve the full range of possible ecosystem services, it is desirable to explore how more extensive tree canopy can be integrated into engineered urban stormwater facilities.

Although the potential of urban forests and other vegetation to mitigate stormwater and provide other ecosystem services is well known, initiatives to increase urban canopy cover have been minimally successful, arguably because of confined rooting spaces in compacted urban soils and frequent below-ground disturbances from construction. To insure load-bearing ability, soils under pavement are intentionally compacted to high bulk densities, typically too high for root penetration. Trees surrounded by pavement therefore have too little suitable soil volume to sustain growth to attain their expected size (Day and Bassuk 1994; Grabosky and Gilman 2004).

Structural soils are mixes of mineral soil and a coarse aggregate that support pavement while allowing root growth. The stone or gravel component forms load-bearing lattices that meet engineering requirements for supporting pavement, while the mineral soil component holds water and air (Grabosky and others 1999). CUSoil (Grabosky and Bassuk 1998), was developed at Cornell University, Ithaca, NY, USA, in the early 1990s as the first soil of this type. Another type of structural soil contains Stalite, a light-weight, heat-expanded slate (Carolina Stalite Company, Salisbury, NC, USA), as the stone component. Structural soil mixes are designed to replace highly compacted mineral soil below pavement, providing additional rooting space beyond the planting “pit” or “cutout”. Since tree roots can easily penetrate structural soil mixes even when compacted to support pavement, this additional rooting space has the potential to allow urban trees to develop larger canopies that could therefore intercept, channel, and transpire more rainfall.

We propose a novel stormwater management facility (SWMF) that incorporates the benefits of trees by using structural soil mixes under pavement (such as parking lots, streets, or sidewalks) so that trees can have greater rooting volume while stormwater can be temporarily stored in the large voids of the mix. From the structural soil reservoir, stormwater can slowly infiltrate into the ground and be transpired by the trees or other vegetation (Fig. 1). Rather than employing traditional stormwater management where runoff is concentrated, collected, and then treated, this system distributes runoff collection and treatment so that the rhizosphere can perform its natural hydrologic function and evapotranspiration can play a larger role. Individual urban sites have multiple uses and functions (e.g., transportation *and* green space *and* stormwater interception; commercial space *and* community center *and* recreation) and coordinating these uses has many benefits (Mitchell 2006). The stormwater mitigation approach presented here creates a multiple-use urban green space that simultaneously provides ecosystem hydrologic function.

Root growth and thus the opportunity to remove stormwater through transpiration in this system (and other stormwater infiltration practices that rely on vegetation) will likely depend on the rate of percolation into the deeper soil regions below the reservoir. In poorly draining subsoils, water from rain events may require several days to infiltrate, whereas other soil types may allow the same rain event to infiltrate within hours. Tree reaction to water table duration is species-specific, and roots of many species cannot survive in submerged soils for long periods. Even short periods of inundation can affect plant biology dramatically (Russell 1977; Whitlow and Harris 1979).

Our overall goal was to determine whether a SWMF that relies on structural soil and trees is practicable: whether trees can grow sufficiently to provide canopy interception of rainfall as well as other ecosystem services and if roots will explore the reservoir sufficiently to remove stormwater. This information will help designers select tree species and place overflow drains to both sustain trees and to maximize the efficiency of stormwater removal in this system, and it may also contribute to the design of other bioretention or raingarden systems. This pilot study specifically addresses the effect of fluctuating water tables in a structural soil reservoir on root growth and distribution and on tree water uptake. Objectives were to answer the following questions:

1. Can two bottomland species thrive in highly porous engineered soils when the root zone is inundated periodically and then drains, as could occur in this proposed system?
2. Do subgrade infiltration rates affect root distribution within the reservoir?
3. Can trees contribute to stormwater removal by withdrawing water from a structural soil reservoir?
4. Do trees that have developed in structural soil reservoirs with different infiltration rates vary in their capacity to remove water from the reservoir?
5. Does green ash root distribution differ in a system using CUSoil® compared to a system using Stalite structural soil mix?

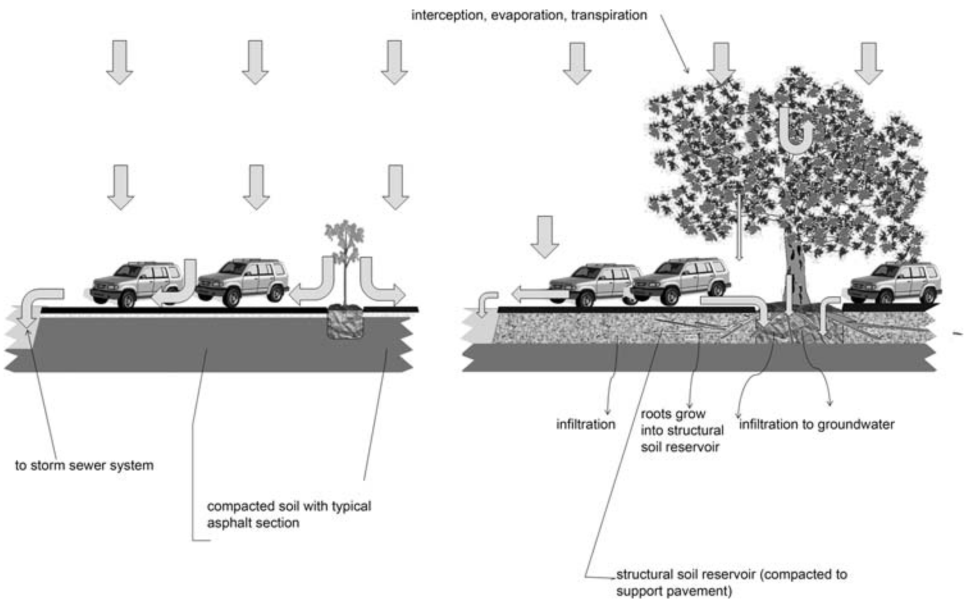

Fig. 1 *Left*: Conventional asphalt parking lot with tree pit. *Right*: Schematic of parking lot with the stormwater mitigation practice described. Note that tree development (and thus canopy interception of rainfall) is enhanced by a larger tree pit and the increased rooting zone provided by the structural soil detention volume

6. What are the implications of the results for SWMF design and other stormwater mitigation strategies?

Methods

Overview

The experiment was conducted at the Urban Horticulture Center of Virginia Tech in Blacksburg, VA, USA (Lat. 37.28° N, Long. 80.46° W). Between May 24th and 26th 2005, three-year-old, bare-root green ash (*Fraxinus pennsylvanica* Marsh. 'Georgia Gem') and swamp white oak (*Quercus bicolor* Willd.), from J. Frank Schmidt and Sons Co., Boring, OR (1–2 cm trunk diameter) were planted in nursery containers (volume = 102.8 L, height = 46 cm, diameter at top = 60 cm) constructed with a series of valves to simulate different depths of rainfall storage in structural soil reservoirs and subsequent infiltration into the subsoil below. The structural soil used contained Stalite (Carolina Stalite Company, Salisbury, NC), a heat-expanded slate, as the matrix aggregate component. CUSoil®, a coarse aggregate-based mix, was used as an additional type of structural soil for green ash. It is anticipated that these matrix materials span a significant portion of the size range that might be encountered in practice.

A placement protocol was developed specifically for this study to assure uniform compactive effort being applied to all treatments. This approach was adopted because of the differences in matrix aggregate used in the experiments and because field equipment cannot be used to compact the mixtures in containers. This is similar in concept to a "method" type field compaction specification, as described later, and is a practical approach considering the wide variation in matrix aggregate sizes and site specific compaction considerations encountered on projects. Structural soil mixes were compacted in two lifts using plywood boards (cut to fit around the tree trunk and inside the container edges) and a Proctor hammer. The hammer (4.54 kg) struck each lift 32 times from a drop height of 60 cm. Dry density achieved using this method was approximately 0.93 g/cm^3 for the Stalite mix and 1.62 g/cm^3 for the CU-Soil mix while saturated water-filled porosity was 31% and 35.5%, respectively. After planting, trees were irrigated daily for 2 months to promote establishment before starting infiltration treatments.

All trees were subjected to one of three treatments that mimicked rapid, moderate, and slow subsoil infiltration rates. Rainfall was excluded and evaporation from the substrate surface prevented by tightly fitting a white plastic covering over the top of the container.

Treatments were assigned in a completely random experimental design with five replications: [(2 species × 1 structural soil) + (1 species × 1 structural soil)] × 3 drainage regimes × 5 replications = 45 total trees. Containers were placed on 1-m centers in two rows. Rows were 1.3 m apart at the center point.

Unless specified otherwise, species were analyzed separately by analysis of variance within the GLM procedure of SAS (SAS, v. 9.1, SAS Institute, Cary, NC, USA).

Container Preparation

Container interiors were painted with two coats of SpinOut®, a copper hydroxide paint (Griffin LLC, Valdosta, GA, USA), commonly used in the plant nursery industry to prevent roots circling along the inside of containers. To allow standardized lowering of the water table, we inserted vinyl tubing (I.D. 1.6 cm) into the container side as close to the bottom as possible and connected another tube vertically with the same height as the container, using polypropylene insert tees. The end of the tube that was inserted into the container was covered with a fine mesh to prevent soil loss and subsequent clogging of the tubes. Outlet valves were installed in the vertical tubing to allow lowering the water table to the desired level. The bottom outlet allowed complete drainage of the container.

Simulated Infiltration Rates

Three drain-and-fill regimes were instituted to mimic typical subsoil infiltration rates: rapid infiltration (2 cm/h), moderate infiltration (1 cm/h), and slow infiltration (0.1 cm/h). This replicates the worst-case scenario where large or repeated storm events fill the reservoir, and water removal is tied directly to infiltration rate of the subsoil. These rates were achieved by filling pots and draining them to the appropriate level according to a daily protocol (Fig. 2). Regimes were begun on July 27th, 2005, suspended during winter (October 27th to April 17th), and then continued until harvest in September and October of 2006. Regimes were suspended during the winter since root and shoot growth had stopped and trees were leafless (i.e., tree biological activity was much reduced during winter dormancy). During the winter months, containers were wrapped with insulation to prevent cold damage to roots and periodically irrigated so that container media was kept moist.

Rapid Infiltration Regime

Containers were filled up on day 1 and completely emptied on day 2. This two-day cycle was repeated throughout the treatment period.

Moderate Infiltration

Containers were filled up on day 1, emptied half way (to a valve 20 cm from the bottom) on day 2, and emptied completely on day 3. This three-day cycle was repeated throughout the treatment period.

Slow Infiltration

Containers were filled up on day 1. Every 5 days, water level was lowered 10 cm to the next valve, until the container was completely emptied out on day 20. This 25-day cycle was repeated throughout the treatment period.

CUSoil

CUSoil was manufactured in general accordance with the specifications by Grabosky and Bassuk (1998). We combined local limestone quarry stone (matrix stone) and a clay loam soil (25.9% sand, 36.9% silt, and 37.2% clay) at a 78:22 dry weight ratio with a small cement mixer. Gelscape®, a potassium propenoate–propenamide copolymer hydrogel (Amereq Corp., New York, NY, USA) was added to the wet aggregate at a rate of 0.03% (by weight) to bind the soil to the aggregate and prevent segregation.

The CU Soil specifications call for a No. 4 coarse aggregate be used as the matrix material. However, No. 4 coarse aggregate is not a standard gradation used by the

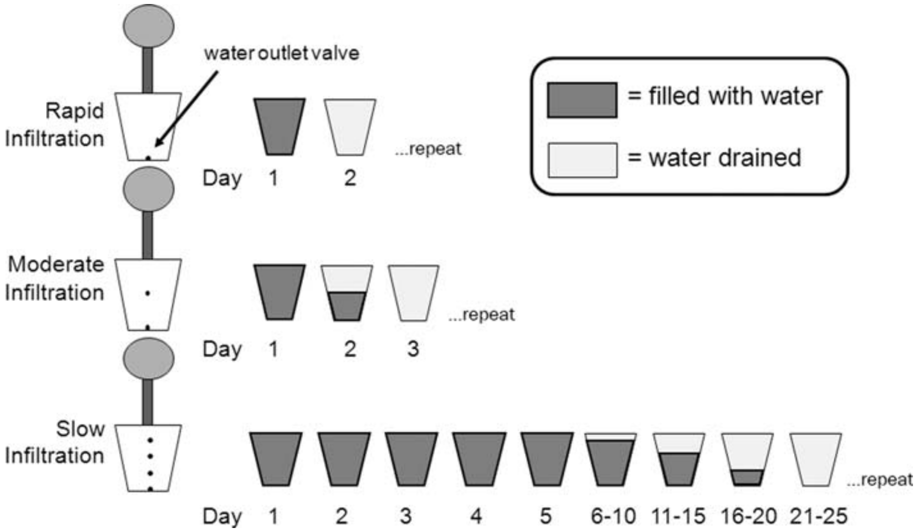

Fig. 2 Filling and draining protocol for simulated water table treatments. *Shaded area* represents water level in pots on each day of the protocol

Virginia Department of Transportation and is therefore not available at our local quarries. We instead used a larger matrix stone consisting of Virginia Department of Transportation No. 357 open-graded coarse aggregate, which has the following distribution of particle diameters: Minimum 100% smaller than 5 cm, 60% ± 2 smaller than 2.5 cm, 20% ± 1 smaller than 1.2 cm and a maximum of 5% smaller than 0.47 cm. The above tolerances indicate that this aggregate can have significant size variations as is true for most coarse aggregates. Laboratory moisture–unit weight relations could not be obtained for the No. 357 aggregate/clay loam mixture due to the large size of the matrix stone. Similar material availability issues and particle size variations will exist in locations outside of Virginia and should be anticipated by designers.

Stalite Mix

Stalite is a heat-expanded slate produced by Carolina Stalite Company, Salisbury, NC, USA. The recommended soil for constructing structural soils with Stalite is a sandy clay loam, mixed to a Stalite:soil ratio of 80:20 by weight (Carolina Stalite Company, Salisbury, NC). We combined two local mineral soils and sand to achieve an appropriate soil texture for the mix (40.0% sand, 28.0% silt, and 32.0% clay). The resulting mix contained a Stalite:soil dry weight ratio of 78:22. Stalite has a particle size gradation consisting of 100% smaller than 2.5 cm, 90–100% smaller than 1.9 cm, 10–50% smaller than 0.95 cm and 0–15% smaller than 0.47 cm. Hydrogel was not needed to prevent segregation during mixing because of the porous surface of the Stalite.

Transpiration Rate

Leaf transpiration rate was measured on 12 days across the 2006 growing season with a porometer (LiCor 1600 Steady State Porometer; Li-Cor Biosciences, Lincoln, NE, USA) in order to capture the overall tree response to treatments. To capture whole-day transpiration rates, we took measurements every 2 h during daylight hours, starting at 08:00 and finishing at 18:00 h on May 9th, 10th, and 12th; July 10th, 12th, 17th, 18th, 19th, 24th, and 31st; August 1st; and September 11th, 2006. Measurements were taken throughout the season; but because whole-day transpiration was measured, scheduling was necessarily limited by rain events, equipment repairs, availability of shared equipment, and availability of personnel. For these reasons, measurements were not evenly distributed across the growing season. The third-to-fifth leaf from the tip of a randomly selected sunlit branch was selected for measurement. Measurements were made on the apical leaflet for ash leaves.

Sap Flow

Sap flow was measured using a heat-balance sap flow system (Flow 32-AO Sap Flow Measurement System, Dynamax, Houston, TX, USA) (Steinberg and others 1989). Eight gauges could be simultaneously logged. Therefore, two to three trees per infiltration regime for each species × substrate combination $(3 + 3 + 2 = 8)$ were randomly selected from among those within reach of the sap flow gauge cables (30 of the 45 trees), and sap flow was logged for nine consecutive days for one species × substrate combination at a time. Measurements were logged for green ash in the Stalite mix from September 5th to 13th, for green ash in CUSoil from September 14th to 22nd, and for swamp white oak in Stalite from September 23rd to October 1st, 2006. One gauge was fitted around the main trunk of each tree with an insulated collar, a heat shield around the gauge, and an aluminum foil wrap as radiation protection. For comparing transpiration rates, sap flow was then standardized to a per-leaf-unit-area basis. The gauge size (they are designed for trunk diameters of 15–19 or 24–32 mm) determines where they may be placed on the trunk. Depending upon the trunk diameter and the tree branching, some limbs were below the gauge. Thus leaf areas from these branches were excluded from the flow-rate-per-leaf-area calculations derived from the sap flow data, but were included in whole-tree transpiration calculations. Data were logged every 60 s and given as a rate per hour. Although only two or three replications were measured per treatment, the sap flow data is robust because it continually measures whole-tree water uptake, instead of sampling individual leaves. Thus, data are valuable since experimental error is reduced, despite the lack of statistical power usually inherent in small numbers of replications.

Leaf Area

Leaf area was measured on subsamples of green ash and swamp white oak to estimate whole-tree transpiration and to standardize sap flow data to a per-leaf-area basis. Leaves were collected separately for the branches above and below the sap flow gauges immediately after completion of the sap flow measurements. Leaf areas of subsample groups (10, 20, 30, 50, 65, 80, and 100 leaves for green ash; and 5, 10, 20, 30, 40, 60, and 80 leaves for swamp white oak) were measured with a Li-3000 Area Meter (Li-Cor Biosciences, Lincoln, NE, USA). Each subsample was dried at 50°C until it reached a constant weight and the leaf area:dry weight relationship determined for each species by linear regression in SAS. The larger subsamples represented 23% and 7% of the average tree whole canopy for swamp white oak and ash, respectively. For swamp white oak, $A_{\text{leaf}} = 47.12 + 85.7\text{dw}$, where A is area in cm^2 and dw is dry weight in grams ($P < 0.0001$, $R^2 = 0.971$). For ash, $A_{\mathrm{leaf}} = 1.28 + 102.9\mathrm{dw}$ ($P < 0.0001$, $R^2 = 0.998$). All other leaves were then dried to a constant weight at 50°C and total tree leaf area and leaf area above all sap flow gauges calculated.

Root Size and Distribution

All containers were laid on their sides, and rootballs gently removed. Measurements started September 18th with green ash in Stalite, followed by the same species in CUSoil®, and then swamp white oak. The width (average of two perpendicular dimensions) and depth of the live root system were measured before washing the stones and soil from the root system. To maintain the same relative distance to the water table levels, the depth was measured from the point on the trunk that was at the same height as the container edge.

Shoot and Root Dry Weight

Trunk diameter was measured at harvest 30 cm above the soil before severing trees at the soil line to separate aboveground and belowground tissue. Live roots were separated and all tissue was dried to a constant weight at 50°C.

Results and Discussion

Tree Biomass

All trees appeared healthy, but there was evidence that tree growth was restricted by the prolonged root inundation in the slow infiltration treatment (Table 1). These differences were primarily observed in swamp white oak, a species considered more sensitive to drought and less tolerant of prolonged root submersion than green ash (Whitlow and Harris 1979; McCarthy and Dawson 1991; Cogliastro and others 1997). During the slow infiltration treatment roots were submerged longer but were also drained for a longer continuous period than other treatments. Swamp white oak was more sensitive to drainage regime; this species had the greatest trunk diameter, root dry weight, and shoot dry weight in the moderate infiltration treatment, although there was no statistical evidence that the differences in root dry weight were due to drainage treatment. Shoot dry weight, however, was strongly affected by drainage regime, with the moderate infiltration rate resulting in more than double the dry weight of the slow infiltration rate (Table 1). This likewise translated into a very high root:shoot ratio (RSR by weight) of 0.96 for slow infiltration trees versus 0.49 for moderate infiltration trees.

The RSR influences the ability of a plant to absorb water relative to its ability to transpire. If the ratio of roots to shoots is too low, water absorption can lag behind transpiration, leading to leaf water deficits (Kozlowski and Pallardy 2002). In the present experiment, swamp white oak may have been unable to fully adapt to the longer flooded and nonflooded intervals in the slow-drainage simulation treatment, so despite greater relative biomass apportionment to the root system, absorptive capacity may have lagged behind above-ground requirements. Green ash, more flood-tolerant than swamp white oak (Whitlow and Harris 1979), exhibited no treatment-induced alteration in biomass allocation between roots and shoots. We observed hypertrophied lenticels on many of the green ash trees, indicating they were adapting to inundation (Gomes and Kozlowski 1980).

Root Distribution

Root distribution is important for tree health and stability, and also will affect whether roots are present at the bottom of the stormwater reservoir where water is presumably held the longest. Swamp white oak trees were grown in Stalite only. But for green ash, where substrates were compared, we found an interaction effect between structural soil type and infiltration regime on rooting depth (Table 2). Green ash trees in the CUSoil® grew deepest in the rapid infiltration treatment compared to trees in the moderate or slow infiltration treatments. Green ash trees in the Stalite mix developed the deepest roots in rapid infiltration, followed by those in moderate and slow infiltration treatments (Fig. 3; Table 2). Unlike the gravel in CUSoil®, individual Stalite stones are highly porous, although many pores are internal and not available for water storage. The difference in pore distribution (i.e., within the stone surface versus within mineral soil) may have changed the water relations and thus have allowed deep root exploration for the moderate and rapid infiltration treatments. Alternatively, the higher clay component of CUSoil® could have played a role in influencing rooting depth. Although there was a clear substrate × infiltration rate interaction, differences in rooting depth patterns between structural soil mixes were not of a magnitude that would influence system design (Fig. 3).

Root systems of green ash in the Stalite mix also grew wider than those in the CUSoil (mean = 49.4 cm and 41.4 cm for Stalite mix and CUSoil, respectively; $P = 0.001$). Root spread was artificially limited in our experiments in comparison to typical root spread of trees in the landscape, which is often at least three times the branch spread (Gilman 1988). The differences we observed likely result from differences between the two substrates in their interaction with container edges, a situation that would not

Table 1 Mean dry weight of roots and shoots, root:shoot ratio, and trunk diameter for green ash (*Fraxinus pennsylvanica* Marsh.) and swamp white oak (*Quercus bicolor* Willd.) grown for two growing seasons in fluctuating water tables simulating slow, moderate, and rapid infiltration rate of subsoils

	Root (g)	Shoot (g)	Total (g)	Root/shoot	Trunk diameter (cm)
Rapid infiltration					
Green ash: Carolina Stalite	525.2 (121.8)	1105.2 (172.9)	1630.4 (292.5)	0.46 (0.03)	3.72 (0.12)
Green ash: CUSoil®	475.3 (73.9)	991.6 (165.9)	1466.9 (224.6)	0.51 (0.10)	3.80 (0.29)
Swamp white oak: Carolina Stalite	348.4 (33.5)	622.6 (98.1)	971.0 (110.4)	0.60 (0.10)	2.65 (0.58)
Moderate infiltration					
Green ash: Carolina Stalite	672.3 (70.2)	1183.3 (118.8)	1855.7 (181.2)	0.57 (0.03)	3.59 (0.23)
Green ash: CUSoil®	568.0 (101.5)	1240.0 (244.0)	1808.1 (326.3)	0.48 (0.10)	3.63 (0.31)
Swamp white oak: Carolina Stalite	455.3 (61.7)	944.8 (168.0)	1400.1 (228.2)	0.49 (0.02)	3.33 (0.17)
Slow infiltration					
Green ash: Carolina Stalite	441.6 (23.1)	763.2 (38.8)	1204.8 (27.0)	0.59 (0.10)	3.24 (0.15)
Green ash: CUSoil®	457.9 (97.3)	825.4 (166.2)	1283.3 (250.6)	0.57 (0.10)	3.30 (0.12)
Swamp white oak: Carolina Stalite	364.5 (87.3)	421.1 (141.0)	785.6 (221.0)	0.96 (0.20)	1.88 (0.17)
			$P > t$		
Green ash: CUSoil®					
Rapid versus moderate	0.459	0.293	0.320	0.799	0.640
Moderate versus slow	0.380	0.085	0.131	0.335	0.304
Slow versus rapid	0.889	0.479	0.590	0.475	0.568
Green ash: Carolina Stalite					
Rapid versus moderate	0.244	0.738	0.509	0.218	0.666
Moderate versus slow	0.073	0.815	0.065	0.799	0.279
Slow versus rapid	0.504	0.152	0.218	0.141	0.135
Swamp white oak: Carolina Stalite					
Rapid versus moderate	0.280	0.130	0.140	0.520	0.012
Moderate versus slow	0.360	0.021	0.047	0.017	0.001
Slow versus rapid	0.860	0.290	0.490	0.043	0.004

Green ash was grown in two structural soil types. $n = 5$. Numbers in parentheses = standard error of the mean (SE Mean). P values were calculated by PDIFF within the GLM procedure of SAS

occur in field installations. CUSoil, which uses rather angular limestone, appeared to interlock more tightly, leading to a more stable overall soil matrix than the Stalite mix, which has more oval-shaped stones. We observed that trees in Stalite mix were easily removed from the substrate, even when root systems were extensive. Perhaps roots were better able to push the Stalite mix aside at the structural soil/container interface. Alternatively, containers were not protected from sun during the growing season and temperatures may have been less hospitable to root growth at the periphery of CUSoil containers. However, we did not measure substrate temperature in this experiment. Temperature may be of interest when these soils are specified under asphalt, where temperatures can be expected to be high in many climates (Graves and Dana 1987). Swamp white oak grew wider for trees in the moderate (mean = 53.3 cm) compared to slow (mean = 40.1 cm) infiltration treatment ($P = 0.088$). Like green ash, rooting depth was treatment dependent, with the rapid infiltration treatment having the deepest root systems (Fig. 3; Table 2).

Transpiration

An overall transpiration rate for the growing season was calculated by combining the whole-day transpiration rates (based on six measurements per tree throughout the day) made on 12 measurement dates over the season. Because it combines a variety of drainage and environmental conditions, this composite leaf transpiration rate provides a means of comparing the overall tree transpiration potential for the growing season. This composite data indicated that trees in the slow infiltration containers transpired at lower rates than the ones exposed to the moderate or rapid infiltration treatment over the growing season as a whole (Table 3). This effect was evident in both species. In the slow infiltration treatment swamp white oak transpired at

Table 2 Treatment comparisons for rootball depth of green ash (*Fraxinus. pennsylvanica* Marsh.) and swamp white oak (*Quercus bicolor* Willd.) grown for two growing seasons in fluctuating water tables simulating slow, moderate, and rapid infiltration rate of subsoils

	Green ash	Swamp white oak
Source of variation	$P > F$	
Infiltration	0.001	0.001
Structural soil type	0.813	NA
Drainage × structural soil type	0.015	NA
CUSoil®	$P > t$	
Rapid versus slow	0.001	NA
Rapid versus moderate	0.001	NA
Slow versus moderate	0.783	NA
Carolina Stalite		
Rapid versus slow	0.001	0.001
Rapid versus moderate	0.007	0.001
Slow versus moderate	0.001	0.077

Green ash was grown in two structural soil types, $n = 5$, P values of contrasts were calculated by PDIFF within the GLM procedure of SAS

Table 3 Mean composite transpiration rates of green ash (*Fraxinus pennsylvanica* Marsh.) and swamp white oak (*Quercus bicolor* Willd.) grown in two engineered soils and subjected to three simulated infiltration rates

	Transpiration, μg/cm²/s	
	Green ash	Swamp white oak
Infiltration rate		
Slow	0.80 (0.05)	0.76 (0.08)
Moderate	1.09 (0.13)	1.39 (0.07)
Rapid	1.14 (0.23)	1.20 (0.08)
Source of variation	$P > \mathrm{F}$	
Substrate	0.282	NA
Drainage	0.002	0.040
Substrate × drainage	0.366	NA
Contrasts	$P > t$	
Rapid versus moderate	0.585	0.455
Rapid versus slow	0.003	0.054
Moderate versus slow	0.001	0.017

Each replication is the mean of diurnal (=6) measurements taken over 12 days in May–September 2006 (=72 total), $n = 5$, swamp white oak was grown in one substrate only, contrast P values were calculated with the PDIFF technique within the GLM procedure of SAS

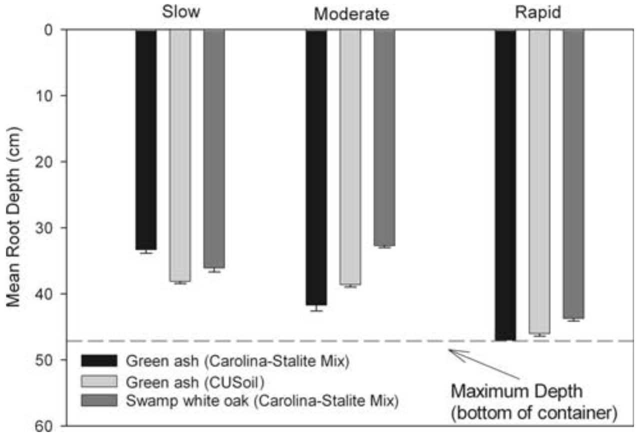

Fig. 3 Root depth of green ash (*Fraxinus pennsylvanica* Marsh.) and swamp white oak (*Quercus bicolor* Willd.) trees after two growing seasons subjected to three simulated subsystem infiltration regimes (slow, moderate, rapid). Bars represent standard error of the mean. $n = 5$ ($n = 4$ for swamp white oak, moderate infiltration). See Table 2 for associated statistics

55% of the rate of the most rapidly transpiring treatment (moderate infiltration) while green ash transpired at 70% of the rate of the most rapidly transpiring treatment (rapid infiltration).

Sap Flow

Sap flow measurements indicated that trees in our experiment transpired between 0.042 and 0.128 g/day/cm^2 (Fig. 4). This is within the ranges described by Kramer and Kozlowski (1960), who summarized transpiration rates for loblolly pine (*Pinus taeda* L.), tulip poplar (*Liriodendron tulipifera* L.), and northern red oak (*Quercus rubra* L.) seedlings as 0.051, 0.098, and 0.125 g/day/cm^2, respectively, under more typical growing conditions. Since the sap flow of the two species in our experiments was by necessity measured during different date ranges (and thus under different environmental conditions), a direct species comparison cannot be made. In addition, low replication numbers reduce statistical power to detect treatment effects. However, sap flow measurements provide real time, whole-tree measurements, providing extensive data for a particular period that can help explain tree response to infiltration treatments. We did not detect that infiltration rate affected sap flow in green ash for either substrate (Fig. 4). However, even with low replication, there was evidence that infiltration rate did affect water uptake rate (sap flow per unit leaf area) of swamp white oak trees. Mean uptake rate was higher in trees subjected to the slow infiltration treatment compared to those in moderate ($P = 0.10$) and rapid infiltration ($P = 0.04$) treatments during the 9-day measurement period (Fig. 4). It should be noted that sap flow measurements for swamp white oak occurred during the latter portion of the 25-day slow infiltration cycle, when containers were mostly drained and the shallow root systems (Fig. 3) would not have reached the treatment water table. This contrasts with the overall depression of transpiration rates described in the composite

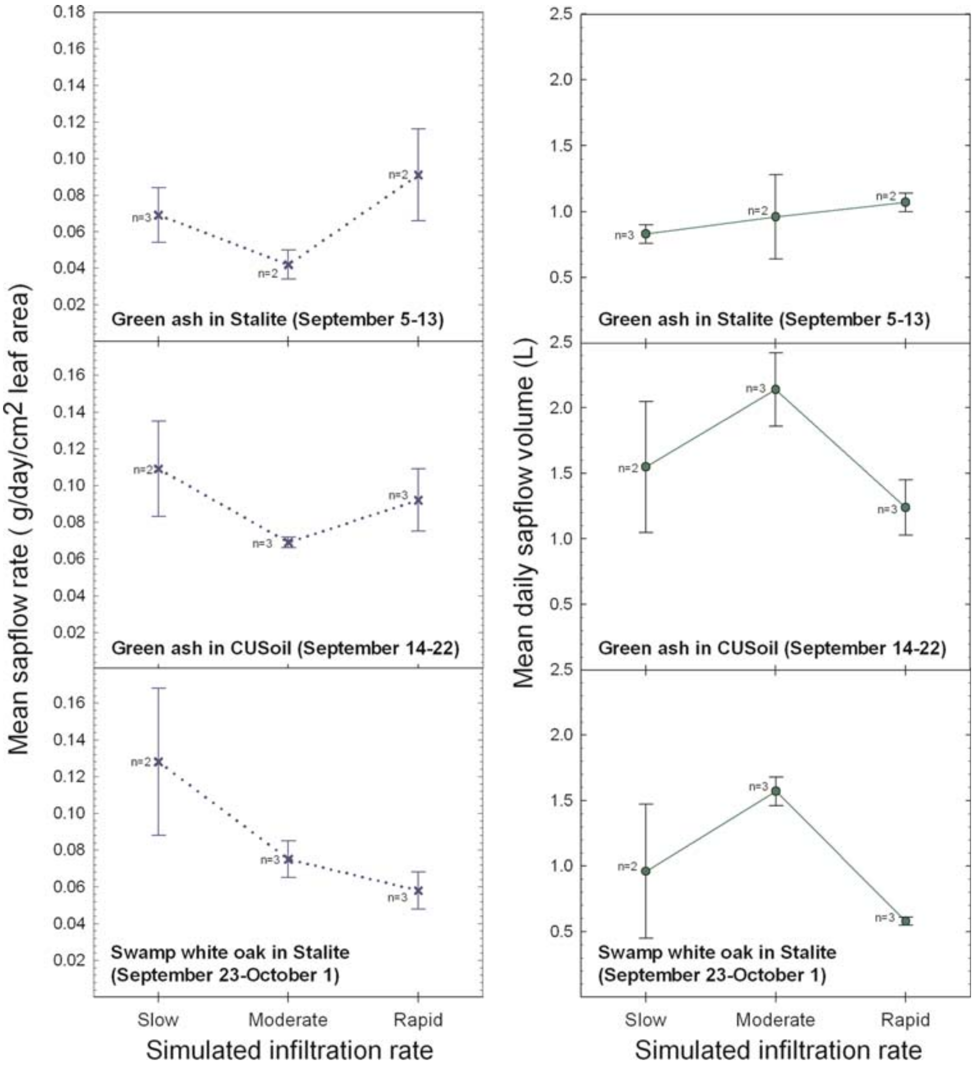

Fig. 4 Whole-tree sap flow for green ash (*Fraxinus pennsylvanica* Marsh.) and swamp white oak (*Quercus bicolor* Willd.) trees logged every 60 s over 9 days after being grown for two growing seasons in engineered soils subjected to three simulated infiltration rates. Sap flow is expressed as a rate per leaf area on the left, and as a total daily volume per tree on the right. Error bars represent standard error of the means. The phase in the drainage regime during each measurement period was as follows: September 5–13 (Slow: days 25, 1–8; Moderate: days 1–3, 1–3, 1–3; Rapid: days 2, 1–2, 1–2, 1–2, 1–2); September 14–22 (Slow: days 9–17; Moderate: days 1–3, 1–3, 1–3; Rapid: days 1–2, 1–2, 1–2, 1–2, 1); September 23–October 1 (Slow: days 18–25, 1; Moderate: days 1–3, 1–3, 1–2; Rapid: days 2, 1–2, 1–2, 1–2, 1–2). See Fig. 2 for description of regimes

measurement (Table 3), suggesting that the relative depression of transpiration rate for the slow infiltration treatment may have occurred predominantly at other phases of the drainage cycle.

Naturally, in addition to transpiration rate, the size of the tree is an important consideration when determining the total amount of water that can be removed from the reservoir, i.e., a large tree will likely remove more water than a smaller tree, regardless of the transpiration rate. There was little evidence for any treatment effects on total sap flow volume for green ash in the Stalite mix (Fig. 4). However, it must be noted that sap flow was measured on these trees at the beginning of the slow infiltration treatment, when roots were mostly submerged. In addition, total biomass of green ash was mostly unaffected by infiltration treatment (Table 1). Total sap flow was greater for green ash in moderate infiltration compared to rapid infiltration ($P = 0.08$) in the CUSoil® and for swamp white oak trees in the moderate infiltration regime compared to those in either slow ($P = 0.10$) or rapid ($P = 0.02$) treatments because of their greater leaf area (Fig. 4). For ash, however, there was no evidence that the greater volume transpired by the moderate treatment was related to drainage regime when compared to the slow treatment ($P = 0.25$), possibly because of limited replication in the slow infiltration treatment dictated by equipment limitations.

Sap flow and porometer measurements for evaluating transpiration have been found to give comparable results in other studies (Ansley and others 1994). To confirm that different results from these two techniques were due to the different measurement times and not the technique, we conducted porometer and sap flow measurements on the same trees at the same time on September 11th for green ash in the Stalite mix, on September 20th for the same species in the CUSoil®, and on September 26th for swamp white oak. Patterns of water use described by both measurement techniques were similar, and there was little evidence for a difference between the treatments for either

Table 4 Effect of simulated infiltration rate on transpiration rates for green ash (*Fraxinus pennsylvanica* Marsh.) and swamp white oak (*Quercus bicolor* Willd.) in a Carolina Stalite-based structural soil on dates when the drainage status for two infiltration rate regimes was identical

Date	Status	Daily mean transpiration rate, μg/cm^2/s			
		Rapid	Moderate	Slow	$P > t$
Green ash					
May 10	Drained	0.564	0.714	N/A	0.279
July 10	Filled	1.235	1.629	N/A	0.211
July 18	Drained	NA	1.610	0.560	0.001
August 1	Half full	NA	1.931	0.812	0.020
July 19	Drained	1.709	NA	0.536	0.001
July 24	Filled	1.279	NA	0.919	0.110
Swamp white oak					
May 10	Drained	0.794	0.733	N/A	0.565
July 10	Filled	1.284	1.320	N/A	0.910
July 18	Drained	NA	1.326	0.804	0.239
August 1	Half full	NA	1.323	0.862	0.272
July 19	Drained	1.318	NA	0.591	0.139
July 24	Filled	1.154	NA	0.795	0.474

$n = 5$ except for July 24 swamp white oak, where $n = 4$

sap flow gauge or porometer measurements on these 3 days (data not shown). Therefore, we believe the differences between overall porometer and sap flow measurements are related to the different times of year and/or drainage stage of individual treatments at the measurement time. Both measurement techniques, however, suggest that a moderate drainage rate will provide the best opportunity for water removal from the stormwater reservoir via tree transpiration.

We compared transpiration rates (as measured with the porometer) on six individual days where two infiltration rates were at the same water level for both species in the Stalite substrate (Table 4). We were therefore able to compare rates at a particular water table level when time and weather conditions were identical. When drained, the slow infiltration trees in the Stalite mix transpired at a slower rate than either moderate or rapid infiltration trees with strong evidence for this being due to drainage treatments in the ash trees. However, this difference was only slight when containers were filled (see July 24th ash measurements), suggesting that differences may be partly related to rooting depth. Rooting depth of slow infiltration trees in Stalite was clearly restricted by inundation (Fig. 3). Nonetheless, moderate infiltration trees transpired at a greater rate than rapid infiltration trees when all containers were filled (see July 10th measurement), indicating there may also be an effect from root adaptation to flooding.

Overall, our measurements resulted in transpiration rates within the normal ranges reported in the literature. Our data also illustrate that larger trees can take up more total water than smaller trees with higher transpiration rates. Wullschleger and others (2000) reported that red maple (*Acer rubrum* L.) trees transpired up to 4.5 l of water per cm of trunk diameter, measured 1.3 m above the ground. A large tree with a trunk diameter of 75 cm could therefore transpire well over 300 l per summer day. However, even if the water uptake of the trees is excluded, rainfall interception, chanelling, and infiltration can still play a significant role in stormwater mitigation. Thus, our proposed system would be a suitable way to collect stormwater, occupying no additional space, and allowing urban forests to handle stormwater in a way that more closely resembles that of their natural forest counterparts.

Conclusions

Overall, our results indicate that a stormwater mitigation approach that integrates full canopy trees and structural soil stormwater reservoirs is feasible. Specifically:

1. Swamp white oak and green ash grew well for 2 years in a system with structural soil and fluctuating water tables, although growth and biomass allocation were sometimes affected by drainage regime. This was particularly evident in swamp white oak where slow infiltration resulted in a 44% reduction of total biomass compared to the trees grown in the moderate infiltration treatment.
2. Subgrade infiltration rates affect root distribution within the reservoir, with rapid infiltration resulting in the deepest root systems. We found that root systems of green ash and swamp white oak trees in soils with a slow infiltration rate were 24% and 17% shallower, respectively, compared to those in well drained reservoirs.
3. Trees with roots confined to such a system transpire within the normal range and therefore can remove water from the stormwater reservoir.
4. Infiltration rate does affect a tree's ability to withdraw water from the reservoir via transpiration, but this effect varies with species. Trees in rapid and moderate infiltration regimes transpired the most water overall, due to differences in both transpiration rate and total leaf area.
5. Root width was affected by substrate, but it is unclear if this is an artifact of the container setup. Furthermore it may not be biologically significant in the field.
6. Overall water uptake can potentially be limited by tree size, rooting depth, and transpiration rate. We recommend that designers choose flood-tolerant species and also insure drainage rates that allow the reservoir to

empty within 48 h to increase the likelihood of good root distribution within the reservoir.

Trees generally grew well and there is great potential for structural soil reservoirs that incorporate trees to be useful stormwater management tools. Although containers allow for controlled replication, they also create artifacts such as restricted rooting volumes and edge effects. Field experiments would therefore be of great value. Both species used in this study are native to bottomlands (Burns and Honkala 1990). We selected green ash and swamp white oak because of their tolerance for both wet conditions and the neutral to high soil pH found in limestone-based structural soils. Although we only tested one species in the two different structural soils, the infiltration–substrate interaction effect on rooting depth suggests that further research would be useful to determine if particular substrates offer advantages for a given hydrologic regime and tree species, especially as future research evaluates a greater variety of species for use in such systems.

Future experiments involving a greater variety of trees would broaden our knowledge about tree behavior in a structural soil reservoir for stormwater management. Roots of some species can penetrate compacted subsoils when saturated and increase infiltration rates (Bartens and others 2008). This may be especially important for deciduous trees because stormwater mitigation by transpiration and interception will be slight when they are dormant (Xiao and McPherson 2003). Canopy cover in many cities continues to decline, and the practice of infill development can further decrease canopy cover and increase impervious surfaces. Therefore, a system that incorporates both paved surfaces and tree canopy is highly desirable.

Design Considerations

We evaluated two kinds of structural soil mixes, CUSoil® and a mix with Carolina Stalite. Both have a porosity of more than 30% when compacted to 95% of Standard Proctor maximum density (Haffner 2007). Therefore, a detention bed of 35 cm depth (i.e., depth below any overflow pipe) can retain a 10–12 cm rain event, assuming that runoff is only collected from the reservoir surface and not the surrounding land area and that the full reservoir capacity is available at the time of the rain event. Water storage in the reservoir can be further controlled via placement of an overflow drain at the desired depth.

Those seeking to implement infiltration methods should anticipate that material availability issues and particle size variations will exist. Mixtures incorporating matrix aggregate falling within the size ranges specified by AASHTO-T-99 (2004), and possibly as modified by AASHTO-T-224 (2004), can be characterized using laboratory methods. An "end result" compaction specification can be used for field compaction control whereby a target value of relative compaction, defined as the ratio in percent of field dry unit weight to the laboratory maximum dry unit weight, and the permissible range of water contents are prescribed. However, when using large matrix material, such as the No. 357 aggregate, it may be necessary to rely on a "method" specification for field compaction. This specification prescribes how each lift of material is to be placed and compacted. A method specification reduces the need for in situ density measurements, which can be problematic given the large size of the matrix aggregate. Data from test sections or experience are often used as the basis for a method type specification.

This study indicates that if water is allowed to stand in the reservoir for long periods of time, rooting depth may be restricted, depending upon the species and the structural soil. Both species in our experiment are native to bottomlands; upland species intolerant of flooding may not survive. Extensive roots to the bottom of the moderate infiltration treatment containers suggest that 48 h is a conservative threshold for maximum inundation time when designing such a system. Exactly how long roots can remain submerged for various species, the long-term effects of restricted rooting depth, and the effects of standing water during the dormant season (when we suspended drainage treatments for our experiments) still need to be determined. Infiltration tests of a specific spot may indicate a very slow infiltration rate, yet alternative pathways for water, such as cracks, can lead to a high overall infiltration rate for the reservoir (Hunt and others 2006; DeBusk 2008). It may therefore be difficult to determine the infiltration rate of the soil below the reservoir without testing it for the entire area.

Species Selection

We would expect trees that tolerate wet soils and high pH, such as the two species in our experiment, to perform best in our proposed system. These are the same characteristics that are desirable in street trees in many cases (Day and others 2000). Because of their greater tolerance for both drought and flooding, green ash was somewhat less affected by drainage treatment overall than swamp white oak. Other appropriate species for an underpavement stormwater BMP that relies on a structural soil reservoir might include red maple (*Acer rubrum* L.), hackberry (*Celtis occidentalis* L.), bald cypress (*Taxodium distichum* L.), and American elm (*Ulmus americana* L.).

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