Shoot and Root Growth of Three Tree Species in Sidewalks[1]

Jason Grabosky[2], Nina Bassuk[3], Lynne Irwin[4], and Harold Van Es[5]
Department of Horticulture, Cornell University, Ithaca, NY 14853

Abstract

Three tree species (*Tilia cordata* Mill. 'Olympic', *Acer campestre* L., and *Malus sp.* Mill. 'Adirondack') were grown in a standard sidewalk pavement profile, an experimental sidewalk profile (SSM), and in the field. Root systems in the paved treatments were harvested after three years to analyze root length, root density, and profile distribution. SSM tree foliage quality (measured by SPAD 502) and shoot extension measured in the second and third years were not different than those of the field control trees. Tree foliage quality and shoot extension were reduced in the standard sidewalk profile. There was an increase in root length of *Acer* and *Tilia* in the SSM profile versus the standard sidewalk profile and an increase in depth of the root zone for all species. The results indicate several advantages in root and canopy growth for street trees grown in the experimental profile compared to the standard sidewalk pavement profile.

Index words: sidewalk materials, street trees, plant establishment, root growth, pavement, urban forestry.

Species used in this study: littleleaf linden (*Tilia cordata* Mill. 'Olympic'); hedge maple (*Acer campestre* L.); Adirondack crabapple (*Malus sp.* Mill. 'Adirondack').

Significance to the Nursery Industry

Investment in street tree planting requires survival and viability to justify planting expenses, yet trees require a larger soil volume than is normally provided. The insufficient soil volume lowers transplant success, vigor and long-term survival. Development of stable materials to establish trees in paved situations should promote more tree planting in urban areas in situations generally not planted due to inhospitable soil conditions. Designed soil materials under the surrounding pavement surfaces have been developed to meet construction needs while remaining horticulturally viable. Use of designed soil materials will promote more successful urban tree planting through better root growth and larger soil volumes, improving the image of urban trees. Increasing tree survival, quality, and life expectance, while maintaining a durable pavement, will result in a healthier urban canopy while increasing the frequency, profitability and value of street tree installations.

Introduction

When a tree is completely surrounded by pavement, the estimated life expectancy of less than 10 years from time of transplanting (18) falls far short of the envisioned design size, potential environmental contributions, and aesthetic functions (9, 17). Quite often, poor plant performance is associated with a lack of root-penetrable soil volumes needed to meet transpiration or nutritional demands (7, 8). Indeed, the compaction levels normally required to support surrounding pavement materials and the selection of the pavement section layer materials often preclude healthy, normal rooting conditions (5, 16, 24). To produce a durable pavement for parking lots, sidewalks, and pedestrian malls, structural requirements to

[1]Received for publication June 2, 2000; in revised form August 29, 2001. Funded in part by a grant from **The Horticultural Research Institute, 1250 I St., NW, Suite 500, Washington, DC 20005**. Plants were donated by J. Frank Schmidt & Son Co. Other contributors included the International Society of Arboriculture, and the Long Island Nursery and Landscape Association.

[2]Assistant Professor. Environmental Horticulture, University of Florida.

[3]Professor. Department of Horticulture, Cornell University.

[4]Associate Professor. Department of Agricultural and Biological Engineering, Cornell University.

[5]Associate Professor. Department of Soil and Crop Sciences, Cornell University.

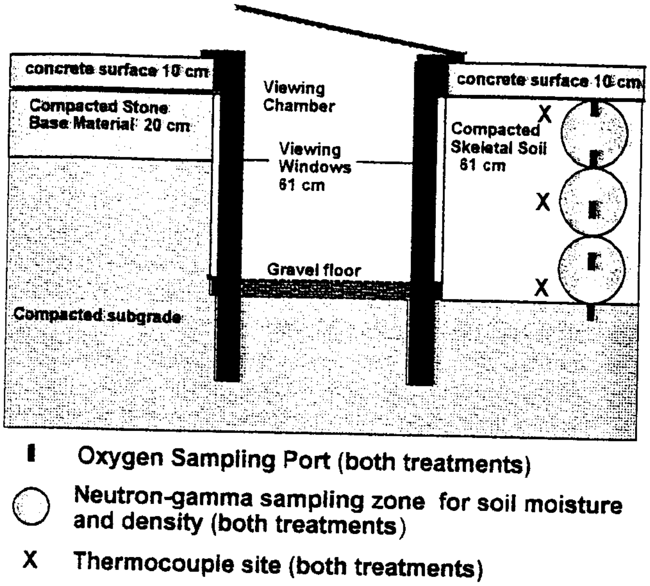

Fig. 1. Cross-sectional plan of the root viewing chamber. The two paved treatments were observed on either side of the viewing chamber. Location of instrumentation testing points are illustrated on the right side. Both sides were equivalently instrumented.

support trucks and large emergency equipment are met by material selection and compaction.

We have focused on a series of gap-graded skeletal soil materials (SSMs) for use in pavement design (12, 14, 15). In SSMs, stones establish a load-bearing lattice or skeleton. In the desired mixture, the soil is 'suspended' between the stones during mixing, placement, and compaction. Loads from pedestrians and vehicles on the material are borne by the stone matrix, without compacting the soil between the stones to a detrimental level. A cross-linked potassium propenoate-proenamide hydrogel is used to help create a uniform mixture (14, 15). SSMs are designed as high-strength pavement base or sub-base materials that remain root penetrable after normal compaction levels specified for pavement construction. Based on positive plant responses in experiments with plants in containers (12, 15), this study was initiated to evaluate plant growth in a simulated working pavement system. Success in SSM design and use could provide a viable root zone to sustain a tree beyond the current life expectancy to match the service life of the pavement surface, infrastructure replacement, or urban renewal without sacrificing the durability of the pavement.

The project served as the first translation of the experimental material into a commercial-scale field application. The site was designed to serve as a demonstration, as well as for data collection, because of the expense involved. Three tree species were chosen to maximize observation opportunities in the new material. The objective of this study was to evaluate tree establishment in a SSM as compared with a standard sidewalk design, and show that tree root zones and durable pavement design are not mutually exclusive.

Materials and Methods

Site design. Two rhizotrons 1.2 m (4 ft) wide, 7.3 m (24 ft) long, and 0.6 m (2 ft) deep, were constructed in Ithaca, NY (USDA hardiness zone 5a). Sidewalks running the length of the viewing rhizotron were constructed against the viewing windows as detailed in previous publications (10, 13) with the standard sidewalk and SSM sidewalk designs on opposite windows. Each sidewalk design (Fig. 1) was installed into an excavated trench equaling the dimensions of the chamber pit. The trench bottom clay soil was compacted to 1.50 Mg cu m (93.6 lb cu ft).

The typical sidewalk installation in central New York state (10, 13) consisted of the compacted subgrade (rebuilt and compacted to 1.66 Mg cu m (104 lb cu ft) in 15 cm (6 in) layers), a 20 cm (8 in) deep stone base (compacted to 2.11 Mg cu m (132 lb cu ft) in two layers), and a wearing surface of 20 MPa (6000 psi) concrete, 10 cm (4 in) deep (Fig. 1).

The second profile was a 0.61 m (2 ft) SSM base (CU Soil®) compacted in 15 cm (6 in) layers to 1.88 Mg cu m (117 lb cu ft) (Fig. 1). The SSM primarily consisted of a crushed gravel of 2–2.5 cm (0.8–1.0 in) (20). The soil used was the silt loam topsoil excavated from the site. A stabilizing hydrogel (Gelscape, Amereq Corp. New City, NY) was also used. The mix design resulted in an 80% stone, 20% soil, and 0.025% hydrogel mixture. The mix design had been previously tested for engineering behavior and plant response (11, 14). The wearing surface was the same concrete as the standard sidewalk.

Construction and post-construction material classification, testing, and relative compactness of the pavement section layers were determined and deemed acceptable using standard American Association of State Highway and Transportation Officials (AASHTO) and American Society of Testing and Materials (ASTM) protocol for construction materials and pavement section design (2, 3, 4, 10, 13). The pavement section layers (Fig. 1) were instrumented in four data collection clusters per trench. Pavement sections were tested for media consistency, rhizosphere oxygen content (5 depths), moisture content and density (3 depths with a nuetron-gamma probe), pH of near-surface media (during installation and demolition), and temperature (3 depths). Previously published work demonstrated that there were no within-treatment differences in the two paved profiles at any given depth, and there were no physical differences in SSM at different depths (10, 13). The same work found no differences in temperature profiles between the two pavement treatments.

Trees were planted into agricultural soil field control plots on three sides of the test area without below-ground viewing chambers (Fig. 2). As a control, the preexisting Niagara silt loam (NaB) was excavated and replaced to loosen the soil volume to eliminate any subsoil compaction layers in the profile; it was then covered with 10 cm (4 in) of hardwood mulch. Three trenches 1.2 m (4 ft) wide, 5.5 m (18 ft) long, and 0.6 m (2 ft) deep, for three control trees each were positioned 3 meters away from the paved treatments.

Plant material and installation. Bare-root 1.8 m (6 ft) tall *Tilia cordata* Mill. 'Olympic', 2.1 m (7 ft) tall *Acer campestre* L., and 1.2 m (4 ft) tall *Malus sp.* Mill. 'Adirondack' were planted on the Cornell campus in 25 cm (10 in) diameter, 30 cm (12 in) depth #5 nursery containers of soil excavated from the rhizotron site. The three species were chosen as representative of commonly used species in the northeastern United States. The same soil was used as the interstitial material in the SSM. Trees were established in the containers for 10 weeks then planted June 20, 1995, into holes held open in the pavement profile by gravel-filled containers of

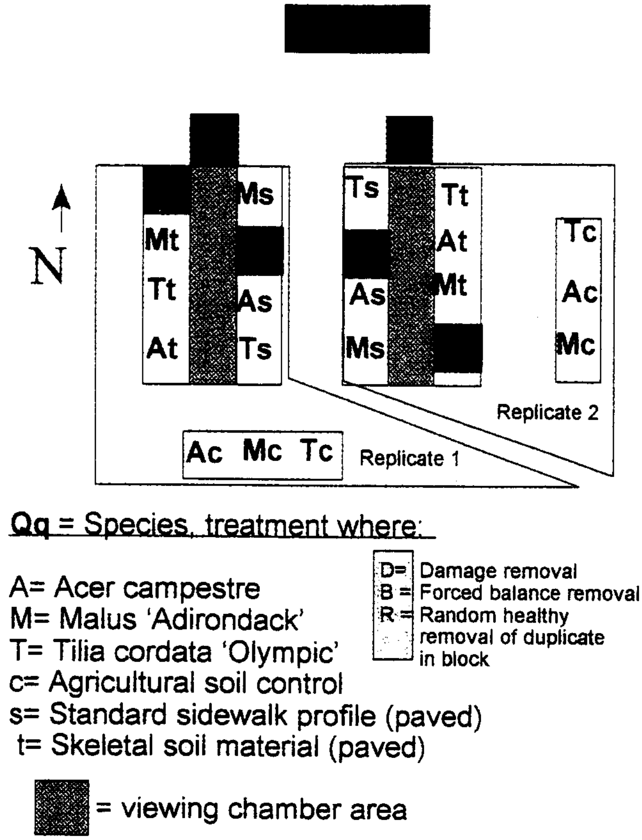

Fig. 2. Aerial plan view of the study site. Three tree species were evenly distributed over the test profiles. The plan shows the rhizotron-control replicates used in the statistical analysis to compensate for plant losses. The final replicates were divided into treatment whole plots, and species as a sub-plots.

equal size. Removal of those containers and replacement with the tree root system prevented compromise of the compaction effort applied to the surrounding profile. A 25 cm (10 in) diameter opening in the concrete was left around each tree. Trees were irrigated daily for one week. No additional irrigation or fertilization was used. The pavement was installed on July 1, 1995.

Statistical design. The initial experimental design was a spatially-balanced random block design (Fig. 2) (25). Animal damage and winter mortality on 4 trees in the third year of the study required the final data to be analyzed as a split-plot design. Two rhizotron pit-control sets served as replicates (Fig. 2). The replicates were partitioned into three treatment plots (SSM, standard sidewalk, and agricultural soil) as each soil profile trench was continuous. The sub-plot for plant response analysis was each of three trees in a treatment block, one of each species. In cases where viable trees were eliminated (3 cases), duplicate trees of a species within the treatment block were identified and randomly eliminated (Fig. 2). This left two replicates per species per treatment.

Statistical analyses were performed on Minitab 11 using general linear model procedures on a split block design with specified error calculations for appropriate F statistic testing. Due to the low replication in the study, pre-planned contrasts were manually calculated with the more conservative Scheffe protection using the whole experiment-wise error at $\alpha = 0.05$ (21, 22).

Shoot growth and foliage quality. Relative chlorophyll content was measured August 18, 1996, and August 18, 1997, with a SPAD meter (Minolta SPAD 502, Spectrum Technologies; Plainfield, IN). SPAD data were used to assess foliage quality. SPAD meters are used as a field diagnostic tool to measure leaf transmittance as a gauge of chlorophyll content or nutrient status in leaf tissue (1, 19). The oldest leaf of the current year's shoot extension were measured on ten separate shoots. Each leaf was measured at three locations per leaf. The mean of the 30 SPAD readings was used in analysis. Shoot extension growth was recorded 3 years after transplanting on August 18, 1997, from a random sample of ten shoots per tree, measured to the nearest 0.5 cm (0.2 in).

Root growth measurements. After manual pavement demolition, root system excavations were performed by collecting all visible roots by hydraulic excavation of the root zone, and wet-sieving during September–November 1998 and March 1999. Each tree was assumed to occupy a space of 1.8 m (6 ft) long, 1.2 m (4 ft) wide and 0.6 m (2 ft) depth (Fig. 3). This volume was divided into 7 zones for root collection. Zones 1–4 divided one half of the root zone into quadrants for testing root distribution. Zone 5 completed harvest of roots penetrating into the given treatment profile. Zones 6 and 7 segregated the roots grown in the original container. Total definition of sections 6 and 7 were lost in the harvest of the first replicates from volunteer excavation and section packaging. While the roots were collected, fine roots (0–2 mm (0–0.08 in)) were labeled by depth, without reference to the container.

Roots penetrating beyond the treatment into the surrounding field soil were excluded from collection, but those roots extending into neighboring tree collection zones within the treatment trench were carefully followed and catalogued under the correct tree individual in the closest root sectoring zone. Roots were collected, bagged and stored in a 2C (35.6F) cooler. The roots were processed by washing to remove soil,

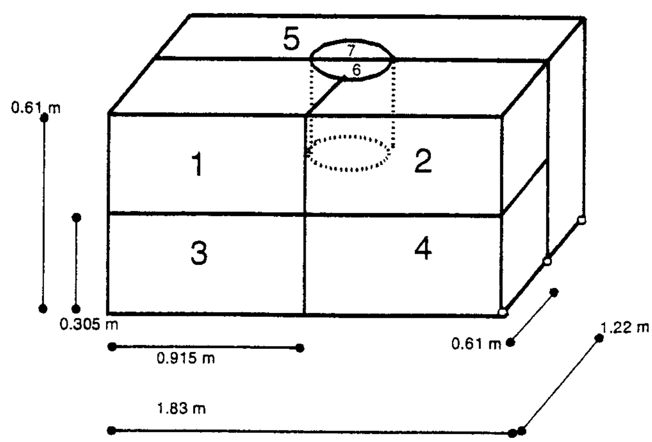

Fig. 3. Sectoring plan of the tree root zone for excavation and root harvest. Zones 6 and 7 were isolated as the original container volume so that root growth into the pavement section materials could be measured.

Table 1. Relative leaf chlorophyll concentration as measured by a SPAD meter from three tree species in two paved profiles versus an agricultural control (n = 2).

Soil profile treatment	*Acer campestre*	*Tilia cordata*	*Malus* 'Adirondack'
Skeletal soil material 1996	42.25a[z]	45.04a	56.69a
Standard sidewalk 1996	33.05b	29.86b	49.74b
Agricultural control 1996	44.06a	37.67c	59.25a
Skeletal soil material 1997	41.91a	42.16a	51.26a
Standard sidewalk 1997	32.84b	27.74b	50.67a
Agricultural control 1997	41.61a	NA[y]	55.77a

[z]Values followed by same letter in a column are not significantly different at $\alpha = 0.05$ among soil profile treatments for that year.

[y]In 1997, insect leaf damage prevented data collection from *Tilia cordata* controls.

Table 2. Shoot extension of three tree species established in two paved profiles and a field grown control (n = 2) measured in 1997 (year 3 of study).

Soil profile treatment	*Acer campestre*	*Tilia cordata*	*Malus* 'Adirondack'
		(cm)	
Skeletal soil material	30.10a[z]	17.56b	32.53a
Standard sidewalk	12.64b	3.68c	20.61b
Agricultural control	34.28a	28.95a	35.43a

[z]Values represent means of ten measured shoots per tree replicate. Values followed with the same letter in a column are not significantly different at $\alpha = 0.05$ between soil profile treatments.

segregating into diameter classes, and measuring volume by water displacement to the nearest 1.0 ml (0.06 in^3). Roots were divided into four diameter classes: <2.0 mm (<0.08 in), 2.0–3.9 mm (0.08–0.15 in), 4.0–5.9 mm (0.16–0.23 in), and 6.0+ mm (0.24 in+) for calculation of root length by dividing the root size class volume by the median cross sectional area per root size class.

Root lengths for each root size class and total length were tabulated and analyzed for treatment differences within each species. Root size classes were converted to percentages of total root length to look for size distribution differences between treatments. Zones 1, 2, and 6 were totaled and compared to Zones 3 and 4 to evaluate root lengths in the top half versus the bottom half of the pavement profiles for each tree. This was further broken down, when possible, to segregate the container roots of Zone 6. Penetration into each profile was calculated as a percentage of the entire root system. Root length densities were calculated as a function of root zone volume by dividing the total root length by the soil volume represented in Fig. 3. Root length densities were calculated as a function of root zone soil surface area by dividing the total root length by the area represented by the 1.8 m (6 ft) long, 1.2 m (4 ft) wide surface assigned in Fig. 3. Both root length density values have been variously reported for other species (6).

Results and Discussion

Canopy response. SPAD data for 1996 of all species established in the standard sidewalk was lower than that of the SSM and agricultural soil control (p = 0.001, Table 1). The 1997 SPAD data for *Tilia* in agricultural soil was lost due to Japanese beetle leaf damage. There were no differences between the SSM and field controls for *Acer* and *Malus*. There were no treatment differences for SPAD measurements of *Malus* in 1997 (Table 1). SPAD values were relatively constant across both years of data collection within species in a given treatment.

Shoot growth was reduced for all three species in the standard sidewalk construction profile (Table 2) compared to the field control and the SSM profile. For *Tilia*, shoot extension in the SSM was less than in the field control. *Tilia* shoot extension of 17.6 cm (6.9 in) in the SSM was still considered satisfactory growth.

Root growth response. Total root length of *Acer* and the *Tilia* was greater in the SSM profile than the standard sidewalk profile (Table 3). No difference was observed with *Malus* (Table 3). Except for the 6+ mm (0.24+ in) diameter roots in *Malus*, the data for each root diameter class followed the same pattern as total root lengths. Root size class distribution as a percentage of the total root system did not change between treatments.

There were treatment differences in the depth of root colonization (Table 4). This was a result of a difference in root zone volume which was limited by the depth of subgrade (Fig. 1). No roots in either treatment penetrated more than 3 cm (1.2 in) into the compacted subgrade. Roots penetrated the entire 61 cm (2 ft) depth of the SSM profile. In the standard sidewalk, the subgrade occurred at 20 cm (8 in) and the bottom of the planting container at 25–30 cm (10–12 in). Those roots placed below the subgrade-base interface in the standard sidewalk profile either failed to penetrate beyond 3 cm (1 in) into the subgrade before terminating or growing upward into the base material. As there were no roots in the

Table 3. Mean tree root length in meters (n = 2) for three species established for three years in two pavement profiles.

	Skeletal soil material	Standard sidewalk
Acer campestre		
0–2 mm diameter	2457	1386
2–4 mm	57	41
4–6 mm	18	10
6+ mm	20	9
Total	2552a[z]	1446b
Tilia cordata		
0–2mm diameter	3431	1801
2–4 mm	84	25
4–6 mm	27	13
6+ mm	39	6
Total	3581a	1845b
Malus 'Adirondack'		
0–2mm diameter	874	748
2–4 mm	33	24
4–6 mm	13	5
6+ mm	5	7
Total	929a	784a

[z]Values followed with the same letter in a row are not significantly different at $\alpha = 0.01$ between soil profile treatments.

Table 4. **Percentage root length in the upper and lower 30 cm layers of three tree species established for three years in two pavement profiles (n = 2).**

	Root length	
	0–30 cm (container included)	30–61 cm
Acer campestre		
SSM	47.3a[z]	52.7a
Standard sidewalk	100b	0c
Tilia cordata		
SSM	51.4a	48.6b
Standard sidewalk	100c	0d
Malus 'Adirondack'		
SSM	68.8a	31.2b
Standard sidewalk	100c	0d

[z]Values followed with the same letter in a column are not significantly different at $\alpha = 0.01$.

Table 5. **Mean root length densities (n = 2) with respect to surface area and root zone volume.**

	Surface area ($cm\ cm^{-2}$)	Root zone volume ($cm\ cm^{-3}$)
Acer campestre		
SSM	11.43a[z]	0.19b
Standard sidewalk	6.48b	0.32a
Tilia cordata		
SSM	16.04a	0.26b
Standard sidewalk	8.27b	0.41a
Malus 'Adirondack'		
SSM	4.16a	0.07b
Standard sidewalk	3.51a	0.18a

[z]Values followed by the same letter in a column are not significantly different at $\alpha = 0.05$ between the soil profile treatment within a species for a given measurement parameter.

30–60 cm (1–2 ft) layer of the standard sidewalk profile (Table 4), the division of the root zone into upper and lower halves did not define vertical distribution of those root systems.

Small differences in root depth distribution were found within the SSM profile for *Tilia* and *Malus*. However, the root measurement included those roots in the original container volume, influencing the root distribution measurement. Where measured, the majority of the penetrating *Acer* and *Tilia* roots (defined as those occurring outside the original planting container) were found in the lower 30 cm (12 in) of the SSM profile. Figure 4 shows a *Malus* replicate during root excavation and demonstrates the tendency for downward root growth which was numerically obscured in the analysis by the inclusion of the root system within the original container volume. Root length density per surface area increased for trees in the SSM profile (Table 5). Due to the difference in root zone depth, root density in the SSM on a per volume basis was less than the standard sidewalk profile (Table 5). The root length density values found in the paved profiles fell within the range of other observations for tree species (6).

Fig. 4. **Root excavation of *Malus* 'Adirondack' in the skeletal soil profile. The original container is marked within the superimposed solid-line box. The wood at the bottom was the viewing window frame and corresponds with the 60 cm (23.6 in) depth bottom of the SSM profile.**

Plant establishment response in the SSM profile was superior to the standard sidewalk design during the second and third growing seasons after transplanting. Shoot extension and foliage quality in the SSM treatment was not different from that of the field controls, which were consistent with a non-restrictive transplanting situation. The larger root systems in the SSM profile were associated with increased shoot extension (Tables 2 and 3) when compared to the standard sidewalk profile. The differences were not significant in *Malus*. The *Malus* 'Adirondack' (a grafted, dwarf cultivar) root systems were also generally smaller than the other two species.

Root growth in the standard sidewalk profile was limited to the upper 20 cm (8 in) of base course material below the pavement but may have been deeper had the base layer been deeper. The depth of base in the standard sidewalk profile was chosen to simulate standard practice in the Northeast United States, and could be considered generous, although in practice base depth varies depending on budgetary constraints and the environment. To foster sidewalk stability, base materials are typically chosen to eliminate organic matter components and to exclude materials that will pass the 75 μm (0.0029 in) sieve, which eliminates clays and silts (5). As such, the typical pavement base material displays a low nutrient and plant-available water regime. The relegation of the tree roots to the base material layer could account for the negative above-ground plant responses in the standard sidewalk profile. Root penetration was deeper in the SSM profile. There was an increase in SSM root colonization coincident with the increase in total root zone volume.

Encouraging root growth deeper below the pavement wearing surface is important. A problematic issue in maintaining street trees is sidewalk displacement from root expansion as the tree matures. Sidewalk damage often is traced to large roots growing just below the wearing surface, such as seen in the standard sidewalk profile of this study. There are also fundamental soil reaction and pavement material service-life issues to be simultaneously considered (23). Not all sidewalks are destroyed by tree root damage; many times, the soil materials in the subgrade negatively impact on sidewalk pavement service life. Concrete ages and wears, consequently pavement cracking and tree root upheaval can occur with older sidewalks where the service life of the sidewalk has not been unduly influenced. The removal of roots in the replacement construction can kill the tree. Once cracked, a sidewalk can be easily lifted as roots radially expand. Moving, training, or encouraging the root zone deeper into the pavement profile would distribute the upward forces generated from radial root growth over a wider area of the wearing surface. This change in root depth could reduce pavement failures and the associated liabilities of pedestrian tripping, structural damage and the need for premature pavement replacement.

Roots in this study may have preferentially colonized the lower zones of the skeletal soil for several reasons. There were no differences in soil moisture, material consistency, and porosity throughout the depth of the SSM profile (10, 18). The SSM was uniformly well-aerated throughout the study. Large diurnal temperature fluctuations in both paved profiles, in excess of 15C (27F), were observed 5 cm (2 in) below the pavement wearing surface where temperatures exceeding 30C (86F) were common (10). Diurnal fluctuations were less than 3C (5.4F) at a depth of 15 cm (6 in), and less than 2C (3.6F) at a 45 cm (18 in) depth in both profiles (10). Given the documented negative impacts of high temperatures on root growth, and the inability of the roots in the standard sidewalk to penetrate the shallow sub-grade interface, temperature was a likely factor in the treatment responses. The implications of the temperature data on root distribution warrant further investigation.

This study demonstrates that the soil material requirements for durable pavement design and horticultural viability are not mutually exclusive. SSMs are a method poised to provide a viable root zone to support long term tree management for health rather than for survival. There are several areas requiring further research, such as long term nutrition in order to optimize SSM mix design, or whether the system will sustain tree growth over time given the relatively low soil content. With a designed SSM able to encourage root growth and healthy tree growth under pavement surfaces, investigations into the long-term growth and mechanical aspects of root growth under pavement can begin.

Literature Cited

1. Abadia, J. and A. Abadia. 1993. Iron and Plant Pigments. p. 327-343 *In*: L. Barton and B. Hemming (Editors) Iron Chelation in Plants and Soil Microorganisms. Academic Press, San Diego CA.

2. American Association of Highway and Transportation Officials. 1995. Standard Specifications for Transportation Materials and Methods of Sampling and Testing, 17 ed. Part II Tests. AASHTO Washington, DC.

3. American Society of Testing and Materials. 1997. Section 4 Construction: 04.08 Soil and Rock (I) D 420–D4914. Annual Book of ASTM Standards. ASTM Philadelphia (editor). American Society for Testing and Materials.

4. American Society of Testing and Materials. 1997. Section 4 Construction: 04.02 Concretes and Aggregates. Annual Book of ASTM Standards. ASTM Philadelphia (editor). American Society for Testing and Materials.

5. Atkins, H.N. 1997. Highway Materials, Soils, and Concretes. Third ed. Prentice Hall Inc., Columbus, OH.

6. Atkinson, D. 1980. The distribution and effectiveness of roots in tree crops. p. 424–490. *In*: J. Janick (Editor). Horticultural Reviews Vol II. AVI Publishing Co., Inc., Westport, CT.

7. Bakker, J.W. 1983. Growing site and water supply of street trees. Groen 39(6):205–207.

8. Craul, P.J. 1992. Urban Soil in Landscape Design. John Wiley & Sons, Inc., NY.

9. Dwyer, J. 1995. The significance of trees and their management in built environments. p. 3–11. *In*: D. Neeley (Editor). Trees and Building Sites: Proceedings of an International Conference Held in the Interest of Developing a Scientific Basis for Managing Trees in Close Proximity to Buildings: Morton Arboretum, 1995. Intern. Soc. Arboriculture. Savoy, IL.

10. Grabosky, J. 1999. Growth response of three tree species in sidewalk profiles. Doctoral dissertation. Cornell University, Ithaca, NY.

11. Grabosky, J. 1996. Developing a structural soil material with high bearing strength and increased rooting volumes for street trees under sidewalks. MS Thesis. Cornell University, Ithaca, NY.

12. Grabosky, J., N. Bassuk, and H. van Es. 1996. Further testing of rigid urban tree materials for use under pavement to increase street tree rooting volumes. J. Arboriculture 22:255–263.

13. Grabosky, J., N. Bassuk, L. Irwin, and H. van Es. 1999. Pilot study of structural soil materials in pavement profiles. p. 210–221. *In*: D. Neeley (Editor). The Landscape Below Ground II: Proceedings of an International Workshop on Tree Root Development in Urban Soils, San Francisco, CA. Intern. Soc. Arboriculture. Savoy, IL.

14. Grabosky, J., N. Bassuk, L. Irwin, and H. van Es. 1999. Structural soil investigations at Cornell University. 203–209. *In*: D. Neeley (Editor). The Landscape Below Ground II: Proceedings of an International Workshop on Tree Root Development in Urban Soils, San Francisco, CA. Intern. Soc. Arboriculture. Savoy, IL.

15. Grabosky, J. and N. Bassuk. 1995. A new urban tree soil to safely increase rooting volumes under sidewalks. J. Arboriculture 21:187–201.

16. Holtz, R.D. and W.D. Kovacs. 1981. An Introduction to Geotechnical Engineering. Prentice-Hall Inc. Englewood Cliffs, NJ.

17. McPherson, E.G., D. Nowak, and R. Rowntree, eds. 1994. Chicago's urban forest ecosystem: Results of the Chicago urban forest climate project. USDA Forest Service N.E. General Tech. Report NE-186. Radnor, PA.

18. Moll, G. 1989. The state of our urban forest. American Forests. Nov/Dec: 61–64.

19. Monje, O.A. and B. Bugbee. 1992. Inherent limitations of nondestructive chlorophyll meters: A comparison of two types of meters. HortScience 27:69–71.

20. New York State Department of Transportation. 1990. Standard Specifications: Construction and Materials: 7.15–7.20 designation #702-02. Office of Engineering, Albany, NY.

21. Neter, J., Knuter, M., Nachtsheim, C., and W. Wasserman. 1996. Applied Linear Statistical Models. 4th Ed. Irwin Publishing, Chicago, Il.

22. Ott, R.L. 1993. An Introduction to Statistical Methods and Data Analysis. 4th Ed. Duxbury Press, Belmont, CA.

23. Sydmor, T.D., D. Gamstetter, J. Nichols, B. Bishop, J. Favorite, C. Blazer, and L.Turpin. 2000. Trees are not the root of sidewalk problems. J. Arboriculture 26:20–26.

24. US Department of the Interior Bureau of Reclamation. 1974. Earth Manual, 2nd Ed. United States Government Printing Office, Washington, DC.

25. van Es, H.M. and C.L. van Es. 1993. Randomization and its effect on the outcome of field experiments. Agronomy J. 85:420–428.