Growth of street trees in urban ecosystems: structural cells and structural soil

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Abstract

Samanea saman and Peltophorum pterocarpum common to the Singapore streetscape were planted in structural soil and structural cell. These were installed with the intention of observing medium to long term plant responses to the various designed soil and cell systems. To verify root colonization in these systems under the sidewalk, root presence was measured using the ground-penetrating radar (GPR) in the fifth year following installation. GPR data indicated widespread colonization of roots in the designed soil and cell system. The highest root signal counts were concentrated deeper in the profile. Trees grown in open spaces were characterized by shallow root systems. Tree physical data identified that trees grown in structural cells had significantly greater growth performances. The observations here provided evidence that these systems served as an acceptable rooting environment when confronted with limited space and soil volumes common to urban environments.

Key words: ground penetrating radar, rooting space, root colonization, structural soil, urban forestry, urban horticulture

Introduction

Long-term tree growth in constrained conditions and compacted soil systems is a major challenge confronting municipalities in urban horticulture management. Much of the published observations and research normally assume a rural-like or relatively healthy soil environment for tree development, but this does not reflect the actual situation in most urban tree installations. Although there is literature available, there is limited published data from urban trees and even lesser information pertaining to specific planting limitations common in urban environments (Lindsey and Bassuk 1991; Grabosky and Gilman 2004; Quigley 2004; Sanders and Grabosky 2014). Noteworthy is also the competing needs of utility services between tree roots, pavement support, telecommunications and lighting infrastructure, and the compacted urban soil condition.

The integration of trees in most urban designs has always been considered as an afterthought. Infrastructure often takes precedence over horticultural requirements so the biotic needs of trees and the soil environment have been established as fillers to plug gaps in the design (Arnold 1993; Kristofferson 1998; Bartens, Wiseman, and Smiley 2006). Given the litany of challenges urban trees are exposed to, the adoption of new tree management technology and practices is vital in our efforts to sustain a healthy urban canopy. Yet, another key challenge faced by urban foresters is the time needed to observe tree growth over an entire life cycle. This will take decades and is therefore not an efficient process.

Tree observation is unlike engineering testing as there is no quick fix to understanding the benefits new technology will provide to urban trees. This paper describes the results of a 6-year study initiated in 2010 to compare a designed soil system (Structural Soil) and the structural cell that was made from polypropylene with load-bearing strength capable of upholding paved sites. Two common tropical species, Samanea saman and

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Peltophorum pterocarpum were used in this study. The designed soil also intended for paved sites, was comprised of 80% compactable stone aggregates accompanied by 20% horticulturally viable soil filling the air gaps between the compacted aggregates (Structural Soil). These designed soil and cell systems were tested against a condition without engineering or technological intervention—an open landscape without physical rooting confinement, comprised of loamy soils (with sand, silt and clay), similar to those used to fill the designed soil and cell systems. The objective of this study was to identify the significant benefits the systems of structural soil and structural cell will contribute to tree growth.

Methods

Site location and description

The study sites were a sidewalk and an open space (1.3448 N, 103.8224 E), located in north east of Singapore. The installation of the structural soil and cells were 1.5 m deep, 100 m length continuous trench of Structural Soil and a similar 100 m of structural cells that supported a concrete sidewalk was installed across the entire length of this study. Another 100 m length of open space (with similar depth dimensions and soil conditions to the designed soil-cell systems) without any physical root restrictions, planted with the same species and same number of replicates was used to establish the significant benefits to tree growth when the designed soil and cell systems were applied.

This installation was built within a working landscape, comprised of a sidewalk installed over the treatment designs (of structural soil and structural cell). It was therefore, not feasible for excavation and testing of the root zone below the pavement. Since root verification under the paved areas had significant importance given that these systems were built to maximise root colonization, the ground penetrating radar (GPR) (Bassuk et al. 2011; Grabosky and Bassuk 2016) was used.

Tree species

The installation of the structural soil and cell systems increased the soil volume, improved the soil quality, and enhanced the root colonization zone by 50% since the space beneath the sidewalk was converted into a root colonization area as well. The sidewalk had a width of 1.5 m, while the width of the planting verge was some 1.2 m (Fig. 1), extending from the building toward the street. Two tree species, S. saman and P. pterocarpum were used. Fifteen trees of each species were planted with a spacing of ~3.5 m between trunks at the study site for the designed soil-cell systems as well as the open space scenario (n = 15/scenario). In all, there were 45 replicates for each species.

Open space

An open landscape area without physical rooting confinement was used to identify the significant advantage the application of the designed soil and cell systems will have on tree growth. The same two species were planted in soil with the proportion of 45–20–35% Sand- Silt- Clay, respectively to a depth of 1.5 m with trees equally spaced at 3.5 m across a 100 m experimental plot sited adjacent to the scenarios of structural soil and cells.

Structural soil

The mix for the structural soil was a gravimetric percentage of 80% granular crushed stone (2–4 cm in diameter), 20% soil (clay loam)—much like the CU-soil described in Grabosky et al. (1998). The soil component was similar to those used in the open space scenario. The pH was at 5.5 and organic matter averaged at 5%. The materials were compacted to 95% AASHTO proctor density. Similar to Grabosky et al. (1998), Grabosky, Haffner, and Bassuk (2009), the density had a range of 1.8–2.2 mg m⁻³. The estimated total porosity was between 25 and 30% v/v with 9% water holding capacity (Grabosky et al. 1998; Grabosky, Haffner, and Bassuk 2009).

Structural cells

The cells were made from recycled polypropylene and each unit measured 1.2 m (L) by 0.6 m (W) by 0.4 m (D) of fixed shape and dimensions. Two units were stacked one on top of the other to achieve a final depth of 0.8 m. Cells were installed according to manufacturer’s specifications given that these were trademark registered units. Each cell was filled with the same loamy soil comprised of sand, silt and clay.

Root colonization

To validate if roots had colonized the spaces under the pavement across the various scenarios, the 400 MHz GPR (Geophysical Survey System Inc., Nashua, NH, USA) was deployed in the fifth year of the evaluation. The GPR was used to avoid the need for coring through the concrete in order to validate if roots had colonized the spaces under the pavement. Using the 400 MHz antenna system, root signals were mapped along three transects running parallel to the trees at 100, 200 and 250 cm from the trunk of the trees toward the building (Fig. 1). The rhizospheric environment for each 100 m transect was reconstructed by joining 15 radar plot files per transect and then splitting the full length into four uniform length segments, each measuring 25 cm. Root signals were mapped between these depths (0–30, 31–50 and 51–70 cm). The data presented in Table 3 indicated the total root signal count per 100 cm sidewalk width. The GPR analysis was developed to map root colonization density using signal density emitted by the antenna. Noteworthy, however, is that this technology cannot discern specific root diameter or directionality even after linking trans- ects. Therefore, the specific tree origins for each root as well as the density of root signals are independent of specific trees. Roots that generated a signal can be assumed to be of a diameter ≥ 0.5 m based on an earlier study by Ow et al. (2012).

Tree growth

Trees were measured monthly after installation. Tree height was recorded using a LaserAce hypsometer and trunk diameter was measured at 1.5 m from the base of the tree diameter at breast height (DBH) using a diameter tape. Growth was tracked using these parameters to infer tree condition and visual ratings associated with foliage quality and overall crown health were also presented in this report. These were similar to the ratings carried out by Wang et al. (2005). Three ratings were averaged as a single observation value. Foliage was graded based on a scale of 0 to 5, where 0 = leaves that are dead or dry; 1 = leaves that are chlorotic and of poor quality; 2 = leaves that are light green and of substandard quality; 3 = leaves that are green and of good quality; 4 = leaves with an even distribution of greenness and of very good quality; and 5 = leaves that are dark green, of excellent quality.
Comparisons between the treatments involving two tree species were analyzed. Slenderness ratios (height-to-trunk diameter) defined as the ratio of total height to diameter at 1.3 m above ground was used as an inference for growth and tracked over time for each species as well as treatment effect on tree health to establish possible allometric relationship patterns. Treatment effect on root colonization was also observed to demonstrate the

### Table 1: Tree diameter, height, and average visual foliar rating in Years 3–5 post-installation

| Year | Species       | Treatment | DBH (cm) | Height (m) | Visual Rating |
|------|---------------|-----------|----------|------------|--------------|
| 2013 | S. saman      | Sidewalk  | 22.3 ± 0.81a | 7.7 ± 0.25a | 3.82 ± 0.31a |
|      | P. pterocarpum|           | 15.6 ± 0.64a | 5.3 ± 0.37a | 3.57 ± 0.26b |
|      |               | Open space| 21.1 ± 0.32a | 7.45 ± 0.34a| 3.68          |
|      |               |           | 14.7 ± 0.41a | 5.1 ± 0.52a | 3.39          |
| 2014 | S. saman      | Sidewalk  | 23.7 ± 0.50a | 7.9 ± 0.31a | 3.85          |
|      | P. pterocarpum|           | 16.9 ± 0.64a | 5.7 ± 0.37a | 3.89          |
|      |               | Open space| 22.8 ± 0.37a | 7.7 ± 0.51a | 3.66          |
|      |               |           | 15.4 ± 0.44a | 5.3 ± 0.29a | 3.41          |
| 2015 | S. saman      | Sidewalk  | 24.2 ± 0.56a | 8.2 ± 0.45a | 3.84          |
|      | P. pterocarpum|           | 18.3 ± 0.64a | 6.0 ± 0.37a | 3.91          |
|      |               | Open space| 22.3 ± 0.72a | 6.2 ± 0.43a | 3.70          |
|      |               |           | 18.5 ± 0.65a | 6.1 ± 0.55a | 3.43          |

*Means and SEs are listed to indicate species-treatment variability. Mean separated using Fisher’s LSD test, P ≤ 0.05. Different letters indicate significance between treatments in a single year. Foliar quality rated on scales of 0–5, where 0 is undesirable quality, and 5 is the most ideal of foliar quality.
Results

All trees survived the 6-year experimental period though some trunks experienced physical damage as a result of weed and grass cutting. There was no significant difference in DBH and height for trees growing in structural soil and in open conditions (Table 1). In contrast, significantly greater DBH and height measurements were observed in trees growing in structural cells (Table 1). These observations were consistent across both species. Visual foliar rating data generally indicated that all trees tended to be healthy but foliar rating for structural cell trees were greater by some 9–16% (Table 1). Basal area data over the experimental duration indicated that the growth of both species benefited from growing in structural cells (Fig. 2). The advantage for growth within structural cells is particularly evident with *S. saman* but less with *P. pterocarpum*. Despite this discrepancy, the growth within structural cells still resulted in sustained increases in trunk basal area for this species over the experimental period (Fig. 2). In contrast, a lower and more gradual development of trunk basal area increment was observed with the same species growing in open conditions (Fig. 2). Trees growing in open conditions achieved a trunk basal area of 0.015 m² by Year 6 while the same species growing in the designed systems of structural soil and cells had reached a comparable size by the fourth year, with *S. saman* as early as the second year (Fig. 2). The slenderness ratio transitioned from thin young tree forms to the more stable slenderness ratio. This was consistent for both species as the trees progressed over the years (Table 2) and there were no significant differences observed between structural soil and cells. Additionally, percent (%) crown dieback was found to be between 30 to 50% less for trees growing in structural cells but this was not significant due to high variability in the data (Table 2).

Root signals were detected throughout the rooting zone beneath the sidewalk in both systems of structural soil and cell as well as in the open condition (Table 3). There was a thorough colonization of roots in the designed soil and cell systems throughout the depths measured (Table 3). A significantly greater signal count was seen in the treatment installed with structural cells (Table 3). The greatest rooting colonization for trees growing in the designed systems was concentrated in the 51–70 cm depth (Table 3) and this was consistent for both species. Conversely, trees growing in open conditions had a higher root signal presence at shallower depths (Table 3).

Discussion

This study represents a medium to long-term observation tracked using a working installation of an aggregate-based designed soil and cell that had the functions of pavement support and root colonization. This study focuses on tree growth in response to an open condition and a paved sidewalk situation installed with the designed soil and cell systems meant to enhance root colonization space. Data suggest that the designed system of structural cells installed in the sidewalk had been beneficial to tree growth and health. While the growth of trees in an open condition without physical rooting confinement and structural soil was found to have significantly slower growth rates. This observed difference may be attributed to greater soil volume available to the trees when structural cells were used. Additionally, the non-compacted rhizospheric conditions would have served as an advantage to tree growth and improved health as well.

The slenderness ratio is used primarily as an index of the resistance of trees to wind throw. The data indicated no significant difference between all the observed scenarios. It was reported in Mattheck et al. (2003) in his study on wind effect on trees, that trees with H/D ratio of ≥50 were considered unsafe if left without any support. This, in turn, was suggestive that all experimental trees were within the desirable range, with a stable slenderness ratio.

The structural cells assisted with load bearing and had 90% void spaces within each cell that was to be filled with horticulturally viable soil. In contrast, the stone-soil mix was comprised of 80% stone which was needed to fulfill pavement load bearing requirements. The effects relating to the shortfall in soil (for structural soil) are likely to be negligible but the eventual slowdown in...
growth is likely as the soil is exhausted (Smiley 2006). This effect may be exacerbated in tropical equatorial climates with year-round growth and without any periods of dormancy. However, a recent report by Grabosky and Bassuk (2016) involving 17 years of structural soil showed that trees grown in structural soil had greater survivorship than trees grown in a lawn. This provided evidence that structural soil remains an economical tool for use when planting space is limiting.

Although previous tree pavement soil studies examined the water availability and mineral requirements of plants in these designed soil and cell systems (Grabosky and Bassuk 1995, 1996; Liesecke and Heidger 2000; Smith 2003; Bartens et al. 2008, 2009; Rahardjo et al. 2008; Pederson 2014), here, a key objective was on the potential for root colonization in these systems. Many of the previous reports are 1–3-year short-term observations (Bartens et al. 2008, 2010; Rahardjo et al. 2008). The short period is in part due to the logistics of experimental design and costs. Publications reporting on medium to long-term research on the designed cell system are still not available though there are few reports on the survivorship and growth associated with the soil system over short, medium and long term durations (Grabosky and Bassuk 1996; Kristofferson 1998; Bühler, Kristofferson, and Larson 2007; Grabosky, Haffner, and Bassuk 2009; Embraud et al. 2009; Grabosky 2015).

Because this experimental site was a working installation, destructive testing was not feasible so root colonization within...
each scenario was studied using remote sensing systems. Noteworthy, however, is that root signals from the GPR antenna cannot denote diameter of individual roots nor can it explicitly point out the direction in which the root is running in the soil. Therefore, the data should be regarded as a presence or absence signal triggered by the antenna. Based on previous work by Ow et al. (2012), a critical minimum root diameter of 0.5 cm will be necessary for the transmission of signal energy. The data were suggestive that the designed soil and cell systems tended to promote deeper rooting while trees in the open conditions tended to have shallower roots. Roots on the surface are likely to damage pavement therefore, the ability to encourage roots deeper down the soil will likely mitigate the damage caused by roots on infrastructure and allow for the coexistence of trees and infrastructure at close proximities in urban conditions. After 6 years, our results on tree physical data and root colonization indicated that there was no significant difference in the response between species. Evidence of differences was only found between the systems which consisted of granular crushed stone and soil versus that of an open space, and that of a structural cell system. The growth and health of trees were significantly improved for those growing in structural cells. The growth and health of trees in the stone soil mix were not significantly different to trees grown in open conditions. The designed soil and cell system effectively encouraged deeper rooting. Although the stone soil mix encouraged deeper rooting, it was apparent that the structural cell system was optimized for tree growth, health and rooting abilities over the longer term (Grabosky et al. 2001; Urban 2008). In contrast, urban open conditions was associated with slower growth, reduced health and shallow root colonization (Bartens et al. 2008; Embrén et al. 2009; Grabosky, Haffner, and Bassuk 2009; Grabosky 2015).

Conclusions

The Structural Soil system provided a root growth substrate that was beneficial to above- and below-ground growth of trees despite the high proportion of stone in the mix. The designed system of structural cells comprised of the same mix of sand, silt and clay had significant growth advantage (above and belowground) over trees growing in structural soil. These results suggest robust ecological fitness in the designed soil and cell systems. They are beneficial for street trees in urban landscapes and can be used by urban foresters to alleviate the stresses experienced by street trees in the urban context. The GPR data indicated widespread colonization of roots throughout the designed soil and cell system across various depths. Higher root signal counts were concentrated at deeper depths. Conversely, trees in open spaces exhibited higher root signal counts at shallower depths. Therefore, when appropriately installed, urban street trees growing in structural soil and cell-based root zone systems can provide desirable growth and environmental services to concrete urban situations. The results here have shown that these systems will allow for sustained, medium term healthy growth of urban trees. In addition, it facilitates the ability for greener and infrastructure in urban cities to coexist in close proximities.

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Conflict of interest statement. None declared.

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