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Urban tree growth and their dependency on infiltration rates in structural soil and structural cells

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ABSTRACT

Expanding tree canopies can be difficult to achieve in built environments because urban land is costly and urban soil inhospitable to vegetation so engineered planting systems offer a potentially valuable tool for achieving sustainable urban forests. Tree water uptake, performance and root distribution were assessed in systems of structural soil and structural cell. Structural soil relies on stone and soil, it is highly porous and designed to support tree root growth and possess pavement strength. The structural cell is made up of rigid structural units with 90% void space which is to be filled with soil. To evaluate tree performance under the conditions of fill and drain regimes in structural soil and structural cell, these two systems were subjected to three simulated infiltration rates. This study was conducted in April 2015 to April 2016 in the tropical equatorial environment of South East Asia. Infiltration rate affected both biomass accumulation and rooting depth. Species and substrate effect was significant for biomass and rooting characteristics but less prominent for transpiration. Biomass was greater for trees in structural cells, and *Pouteria obovata* was particularly sensitive to prolonged inundation. Rooting depth was always higher in the rapid infiltration indicating the negative effects inundation had on this parameter. Root system in the structural cell was deeper while those in the structural soil were wider. *Samanea saman* had better adapted to the drain and fill regimes, and this was despite *Pouteria obovata* being a coastal species and was expected to be flood tolerant. Species and substrate effect was weak (R^2 ranging from 0.20 to 0.28) but moderate drainage consistently led to higher transpiration. We conclude that structural soil and structural cell are potential solutions and provide a tool to overcome suboptimal urban growing conditions. The application of these solutions will allow for seamless integration of greenery with urban infrastructure.

1. Introduction

Enhanced urbanisation results in increased hard and impervious surfaces which thus increases the likelihood of compacted soils and waterlogged conditions (Boland et al., 1993; Paul and Meyer, 2001; Jantz et al., 2005; Tu et al., 2007). Urbanisation is expected to continue to increase (Velarde et al., 2004), therefore, the ability to provide ideal growing conditions for trees and shrubs are becoming more difficult (Foley et al., 2005). The tangible environmental functions of an urban forest such as shade and the effect of reducing ambient temperature (Yan et al., 2012; Wang et al., 2015), is well documented and the environmental, physiological and psychological benefits brought about by trees has become more evident in recent years (Nowak et al., 2014). Although the potential of urban forests and other vegetation to mitigate the negative effects brought on by the urban environment is well known (Roy et al., 2012), initiatives to increase urban canopy is often minimally successful (McGree et al., 2012), arguably, a result of confined rooting spaces, compacted urban soils and frequent below-ground disturbances involving utilities (Grabosky and Bassuk, 2016).

Soils under pavement are intentionally compacted to high bulk densities to enhance their load bearing abilities, in most instances however, the compaction is too high and so obstructs root development. Trees surrounded by pavement have limited usable soil and water, alongside reduced aeration to sustain growth (Day and Bassuk, 1994; Grabosky and Gilman, 2004). A solution termed as structural soils are comprised of clay soil and a coarse aggregate that support pavement while allowing root growth (Grabosky and Bassuk, 2016). The stone component forms load-bearing units that meet engineering requirements to support pavement, while the soil component provides the nutrients (Grabosky and Bassuk, 1998; Grabosky et al., 1999).

Conversely, structural cells are rigid polypropylene structures of fixed shape and size, designed with 90% void space meant to accommodate soil (DeepRoot Green Infrastructure, LLC). The key advantage this system has over the structural soils will be the greater content of organic soil to sustain growth. This system has no requirement for stone as the load from the pavement is borne by the structure.

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Both the structural soil and structural cell were designed to replace highly compacted soil below the pavement, providing additional rooting space beyond the planting area. Tree roots have been shown to effectively penetrate these systems (Grabosky and Bassuk, 1998; Grabosky et al., 1999). Therefore, these systems provide additional rooting space to allow urban trees to develop to their fullest potential.

Additionally, these systems can be installed in a variety of scenarios from parking lots, sidewalks, plaza spaces, through to roadways. Therefore, the application of these systems supports the creation of multi-functional urban green spaces for environmental, social and economic benefits. Apart from above-ground growth aspects (such as trunk and shoot development), the benefits also extend into the rhizosphere. This is achieved through the avoidance of waterlogged conditions which is dependent upon the rate of percolation, and the ability of the structural cell and structural soil to channel water into deeper soil regions. In poorly drained subsoils, water from rain may take up to several days or weeks to infiltrate, whereas porous soil types may allow rain to infiltrate within hours (Mitchell, 2006; Wang et al., 2008) A tree's response to the duration of inundation is species-specific hence the need to study the responses of different tree species to inundation through drain and fill regimes. Roots of many species cannot survive in submerged soils for long periods so, even short periods of inundation can affect plant survivorship (Russell, 1977; Whitlow and Harris, 1979).

This study was set up to address the following questions:

1. Is there a difference in the growth potential of two tropical tree species in the structural cell system, and the highly porous engineered soil (structural soil)?
2. Is there a difference in the rooting potential for the two species in the structural cell, and structural soil? How do they respond when the root zone is inundated periodically?
3. What are the implications and/or benefits for urban forests when these systems are installed?

While there have been earlier reports (Bartens et al., 2009; Grabosky et al., 2009) on infiltration rates in structural soil and the benefits associated with tree and root growth presented in the literature, there are so far no reports that delve into similar effects relating to structural cells, and also no comparison made between the systems of structural soil and structural cells. Additionally, the novelty of this research lies in the species and climatic conditions. Related work had been carried out primarily in temperate regions with distinct seasons and involving temperate species. Here, the research presents a stark contrast involving tropical species in a tropical equatorial climate, supplementing the existing knowledge on temperate species, and paving the way for an in-depth understanding of the feasibility of such systems to be applied in urban environments as a mitigating strategy against sub-optimal growing conditions.

2. Methods

2.1. Site and tree

The experiment was conducted at the Polytechnic Academic Institution, Singapore (1.3787° N, 103.8493° E), between April 2015 and continued till the same period the following year. For each species, the experiment was comprised of 6 replicates each for structural soil and structural cells, and 2 replicates each per infiltration/drainage scenario. Both species had contrasting growth characteristics whereby *P. obovata* was a coastal tree and hence considered to be more tolerant of prolonged root submersion. While *S saman* grows best under dry soil conditions. Two-year-old bare-root trees (1–2 cm trunk diameter) of similar sizes were selected and planted in customised containers that measured 3.0 m (L), 1.5 m (W), 1.2 m (D), installed with outlet valves to control rainfall discharge so as to simulate the various infiltration rates. Perforations in and around the container were lined with fine mesh to prevent soil loss and clogging.

2.2. Structural soil

The structural soil used was an aggregate and soil component, mixed thoroughly. The aggregate component was made up of coarse aggregates (2–4 cm in diameter) while the soil component was that of clay loam in the proportion of 8: 2 parts, respectively − much like the CU-soil described in Grabosky and Bassuk (1998). The clay loam soil used in this mixture was primarily sand and clay in the proportions of 45-20-35 Sand- Silt- Clay, respectively. The pH was at 5.5 and organic matter averaged at 8%. The structural soil mix was compacted in four lifts using plywood boards (cut to fit around the tree trunk and placed inside the container). Compaction was achieved aided by a mini walk behind compactor. Dry density achieved using this method was approximately 1.77 g/cm^3 while saturated water-filled porosity of the mixture was 59%

2.3. Structural cell

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). Two units were stacked one on top of the other to reach a depth of 0.8 m. Cells were installed according to manufacturer's specifications given that these were trademark registered units. The total area and soil volume for each tree that was grown in cells were 2.88 m^2 and 2.3 m^3, respectively. Each cell was filled with the same loamy soil (above) comprised of sand, silt and clay. The soil within each cell was lightly compacted with hand shovels.

2.4. Simulated infiltration rates

After planting, trees were irrigated daily for a month to promote establishment before the commencement of treatments. Two trees per species were subjected to one of three treatments that simulated rapid, moderate, and slow subsoil infiltration rates. The containers were kept away from rain and surface evaporation was prevented by fitting a plastic sheet (with small perforations for ventilation) over the top of the container. Treatments were assigned in a complete randomised design. Unless specified otherwise, species, system and substrate types were analysed separately by analysis of variance within the GLM procedure of SAS (SAS, v. 9.1, SAS Institute, Cary, NC, USA).

2.5. The three drain-and-fill regimes were comprised of the following infiltration rates (Fig. 1)

a. Rapid Infiltration

Containers with structural soil were filled on day 1 and completely drained by the second day. This two-day cycle was repeated throughout the treatment period. Containers with structural cell were filled on day 1 and completely drained by the third day. This three-day cycle was repeated throughout the treatment period.

b. Moderate Infiltration

Containers with structural soil were filled on day 1, drained half way (to a valve positioned 30 cm from the bottom) on day 2, and drained completely on day 3. This three-day cycle was repeated throughout the treatment period. Containers with structural cell were filled on day 1, drained half way (to a valve positioned 30 cm from the bottom) on day 3, and drained completely on day 4. This four-day cycle was repeated throughout the treatment period.

c. Slow Infiltration

Containers with structural soil were filled on day 1 and completely drained itself out on day 11. This 11-day cycle was repeated throughout the treatment period. Containers with structural cell were filled on day 1 and completely drained itself out on day 16. This 16-day cycle was repeated throughout the treatment period.