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# Urban Stormwater Management: Can Tree Roots and Structural Soils Improve Hydraulic Conductivity into Compacted Soils?

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**Abstract.** Typically, surface precipitation runoff is a key source of flooding and water pollution in urban communities, and the costly and time-consuming process of installing bio-retention basins is one approach to overcoming these challenges. The implementation of structural soils in bio-retention basins designed to receive and retain stormwater provides these systems with additional functions to bear loads and facilitate tree root growth and exploration. The channels that tree roots produce as they grow can also aid in the flow of water down the soil profile. In this study, the potential for tree roots to penetrate compacted soils and increase rates of hydraulic conductivity were examined alongside the use of structural soil in the context of urban stormwater systems. For the first experiment, *Pouteria obovata* and *Calophyllum soulattri* together with a control (without tree) were placed in cylindrical planting sleeves surrounded by compacted clay loam at two compaction levels (bulk densities of 1.45 g $cm^{-3}$ and 1.66 g $cm^{-3}$). Roots of both species penetrated the compacted soil, and hydraulic conductivity was increased by an average of 50%. In the second experiment, the same species were grown in structural soil, and a geotextile separated the compacted soil (bulk density of 1.66 g $cm^{-3}$) from the structural soil (compacted). A greater number of roots as well as larger root diameters from *Pouteria obovata* penetrated the geotextile, and hydraulic conductivity was enhanced twofold when compared to the controls that had no trees. Growing woody rooting plants and installing structural soils within urban stormwater systems may confer benefits of increased water infiltration and enhanced root development, alongside potential overall improvements to tree health for stormwater control systems in urban environments.

**Keywords.** Hydraulic Conductivity; Root Penetration; Soil Compaction; Structural Soil; Urban Stormwater Systems.

## INTRODUCTION

Urban runoff management is critical to slow down the damaging environmental effects of urbanisation and increasing population growth (Barron et al. 2013; Verbeiren et al. 2013). Human settlements are often concentrated around water sources, hence, such areas are often highly urbanised (Domene and Sauri 2006). Urbanisation increases urban runoff alongside related problems such as reduced groundwater recharge, habitat destruction, marine animal kills, and beach pollution (Van der Bruggen and Borghgraef 2010). The consequences are often altered stream or river hydrology, increased suspended sediment concentrations, downstream sedimentation, and increased incidence of flooding (Semadeni-Davies et al. 2008). Many cities are using innovative green infrastructures such as stormwater control systems that mimic the way nature collects and cleanses water. For example, in northeast Philadelphia, a small park that used to be flat was converted into a sloping terrain that had a low-lying area lined with plants to gather and funnel stormwater through the area (Stutz 2018). Sustainable drainage systems (SuDS) possess several functions, from pavement and subgrade used for infiltration to reduce the risk of flooding (Davis et al. 2001), to recharging groundwater to help prevent drought (Dasch et al. 2012), providing valuable habitats for wildlife in urban areas, and improving water quality (Berland et al. 2017). In addition, SuDS can optimise space utilisation and allow for infiltration to occur over large surface areas. SuDS can also include the retention of stormwater under pavements in subgrade reservoirs comprised of beds of gravel. The aim is to increase infiltration, and this approach is unique in that it concentrates runoff in detention basins while traditional stormwater management allows for distributed infiltration.

In rural and forested environments, rainwater is stored within the forests and wetlands and then slowly infiltrates into the ground. By contrast, urban infrastructures such as buildings, roads, and footpaths channel water very quickly away as runoff with minimal water flowing into unpaved soils (Pitt et al. 2008). This is expected to be exacerbated by increased rainfall intensities and rainfall volumes resulting from climate change (Mullaney et al. 2015). There is also the problem of waste and pollution transported by stormwater that poses quality issues (Barbosa et al. 2012). Also important is the need for sustainable yet flexible urban stormwater management approaches—for example, poorly maintained SuDS can pose a flood risk themselves (Annicka et al. 2013). SuDS are built to mimic nature and manage localised precipitation. SuDS can be more sustainable than traditional drainage methods and can be built and designed to carry and slow down runoff before it reaches the city's drainage network. In addition, they store water while allowing some to infiltrate into the ground, while more water can be evaporated or lost via vegetation through evapotranspiration (Grey et al. 2018). SuDs can therefore be regarded as environmentally beneficial drainage systems that urban cities can use to efficiently and sustainably drain surface water while reducing pollution and improving the water quality of local water bodies (Nowak et al. 2008).

## Urban Trees in Stormwater Management

In urban environments, urban forests are an effective stormwater management strategy where precipitation is intercepted by the canopy. Likewise, trees direct the flow of water into the ground through trunk flow (Armson et al. 2013), and roots absorb stormwater (Bartens et al. 2009). For example, in a report by Xiao and McPherson (2003) it was concluded that individual tree canopies can intercept approximately 80% of a 24-hour rainfall (20 mm) under full foliage conditions (Xiao and McPherson 2003). However, the urban conditions may not permit such optimum canopy growth given the harsh growing environments (e.g., reduced rooting volume). Likewise, bioswales and rain gardens require frequent maintenance. But the inclusion of trees and structural soils under pavement can effectively function in confined, impervious conditions. This is because the structural soil profile normally occupies about 0.6 m of depth and is compacted to meet engineering standards that typically hold streets and car parks (Grabosky and Bassuk 1998). Despite the high levels of compaction, the structural soil profile is still able to possess high porosity of approximately 30% to 40% (Grabosky and Bassuk 1995). Hence, structural soil profiles can store stormwater and maintain tree growth alongside root extension. In turn, the improved growth conditions may improve urban runoff through rainfall capture in large, overlapping canopies even before the rain reaches the ground surface.

## Roots and Hydraulic Conductivity

The flow of water along tree roots has been previously documented in reports by Johnson and Lehmann (2006) and Bejan et al. (2008). In addition, earlier work by Bramley et al. (2003) using containers confirmed that hydraulic conductivity was 15 times faster when trees were present as compared to those without trees. Rosolem et al. (2002) and Clark et al. (2003) also highlighted the importance roots conferred to hydraulic conductivity, where water flow was decreased in compacted soils as a result of limited root penetration and smaller roots. Therefore, this study was set up to evaluate the potential of roots to direct the flow of water through compacted soils and how this might increase hydraulic conductivity.

Compared to canopy or trunk interception of water, the ability for tree roots to improve infiltration rates has received much less attention, hence, less is known about their benefits, especially in compacted soils, which is an area covered in this study. The intent was to establish an understanding of hydraulic conductivity, not just within, but also alongside the stormwater control systems. Conversely, much more is known about the benefits of structural soil for enhanced rooting in spite of limited growing spaces (Ow and Ghosh 2017a, 2017b). Therefore, the aim of this study was to use a SuDS reservoir and structural soil to increase the rooting volume for the tree and at the same time examine if the flow of water through compacted soils could be improved via rooting channels. If tree roots were observed to benefit infiltration, the incorporation of trees within bioswales and rain gardens could be regarded as a critical element during the planning and design stages. Therefore, the outcomes of this study will contribute to current as well as future stormwater retention best management practices. The experiments were conducted under controlled conditions and they took place concurrently across a 1-year period with the objective of improving our understanding of the effects of trees and roots on the hydraulic conductivity of urban soils.

## MATERIALS AND METHODS

### Experiment 1: Controlled Compacted Soil Study

Experiment 1 was conducted in controlled greenhouses where bare-root trees of *Pouteria obovata* and *Calophyllum soulattri* were installed into 25-L containers alongside a control which had no tree for 4 months. In June 2018, 1.5-year-old seedlings of both species were placed in a cylindrical planting sleeve comprised of 2.5 L of mulch and each positioned in the middle of 25-L containers that had compacted soil (Figure 1). *Pouteria obovata* and *Calophyllum soulattri* were selected for this study because they provided a good comparison between a fine- and coarse-rooted species. In addition, these were trees that were commonly grown in urban tropical-equatorial environments where this study was carried out and were ideal candidates for SuDS due to their ability to grow well along natural cliffs, along the edges of rivers and sandy shores, as well as in mangrove forests. The compacted soil was comprised of 12% sand, 35% silt, and 53% clay. Two compaction levels achieved using a proctor hammer were used in this study (bulk densities of either 1.45 g $cm^{-3}$ or 1.66 g $cm^{-3}$). All containers (those with trees and those without) were irrigated daily until the soil was unable to absorb any additional water. Eighteen containers with three replicates and three treatments (two species and one without tree) and two compaction levels were arranged in a complete randomised design (3 × 3 × 2).

#### Soil Compaction and Inserting of Trees into Containers

A round, 2-cm-thick wooden board was laid inside the 25-L containers on top of the soil and struck from a height of 50 cm 15 times to achieve compaction level 1, which had a bulk density of 1.45 g $cm^{-3}$. Similarly, to achieve compaction level 2, which had a bulk density of 1.66 g $cm^{-3}$, the board was struck 25 times. The compaction levels were achieved using a 5-kg proctor hammer, similar to the methodology detailed in Bartens et al. (2008). These compaction levels were chosen as they tended to restrict root growth in urban soils (Unger and Kaspar 1994; Clark et al. 2003). Next, a pipe (12-cm diameter) was inserted into the middle of the container. It was struck 15 and 25 times using the same method to achieve compaction levels 1 and 2, respectively. Thereafter, the pipe was removed, and a 6-cm-long (12-cm-diameter) poly

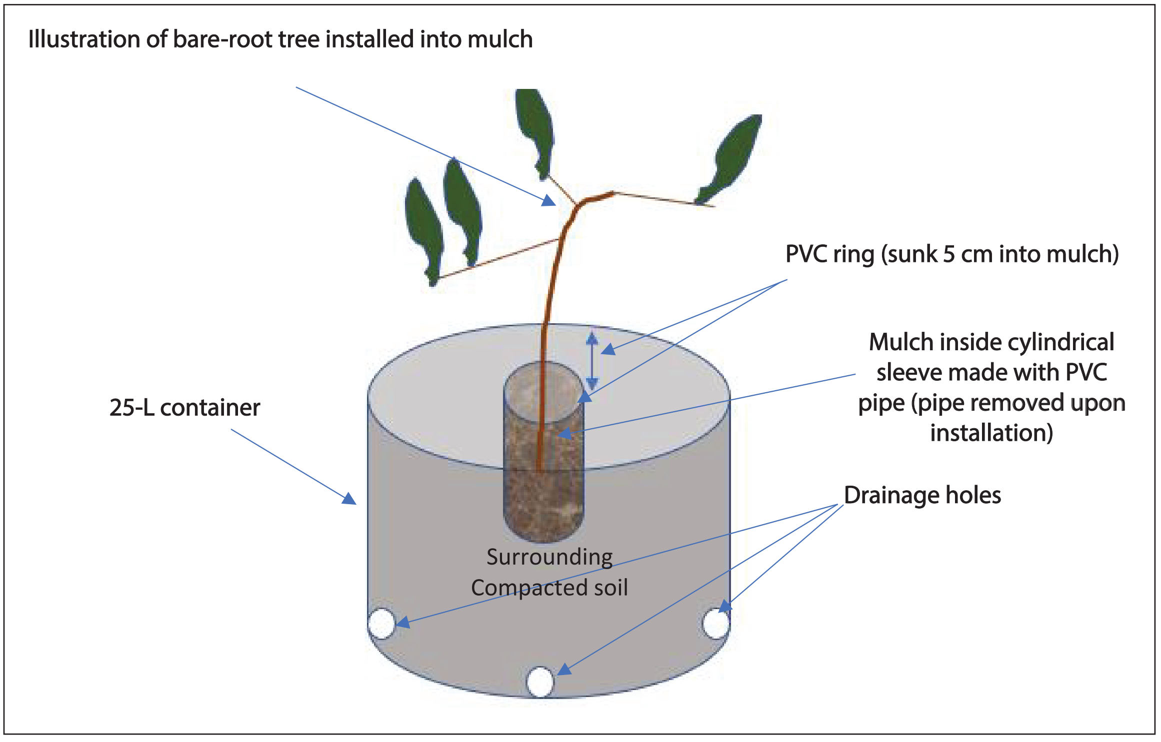


**Figure 1. Schematic illustration of experimental set-up for Experiment 1: compacted soil study (not to scale).**

vinyl chloride (PVC) ring was inserted 5 cm beneath the soil surface, and the tree was planted with mulch filling the space created by the pipe (trees were absent in the control).

### Hydraulic Conductivity

Because saturated flow through the soil will provide a more consistent measurement of conductivity, the soil in each container was flooded to saturation before measurements were made. Hydraulic conductivity was measured on 6 occasions, once every 2 months in the year 2019. Thereafter, 1 L of water was poured into the planting sleeve, and the time required for the water to infiltrate (until no water was found on the mulch surface) was determined. As the surrounding soil was saturated, this measurement provided the saturated hydraulic conductivity for a specific area (across the entire container).

### Root Measurement

Vertical and horizontal root growth within the compacted soil was determined by cutting 2-cm-thick slices from the bottom and sides, and root counts and diameters were measured. This was done after the final measurement in December 2019, and the methodologies were adapted from Blessing and Dana (1987). Loose soil was removed from cut roots or root tips during counting. The bottom and sides had surface areas of approximately 700 $cm^2$ and 750 $cm^2$, respectively. This approach was similar to Bartens et al. (2008). The bottom and side slices also included roots present in the mulch, and counts were measured on a per-unit-surface-area basis.

## Experiment 2: Structural Soil Study

In this experiment, which was conducted in controlled greenhouses, 100-L containers without drainage holes were used. Drainage was enabled through an 8-cm-long (3-cm-diameter) PVC pipe outlet at the bottom of the container. High density polyethylene (HDPE) mesh was placed over the drainage outlet to reduce soil loss, and sealant was applied to avoid leakages. A single drainage hole (5-cm-diameter) was drilled 6 cm from the top of the container (Figure 2). This was carried out for each pot, and the aim of the drainage hole at the top of the pot was to ensure that the water was maintained at a constant level for consistent hydraulic conductivity monitoring.

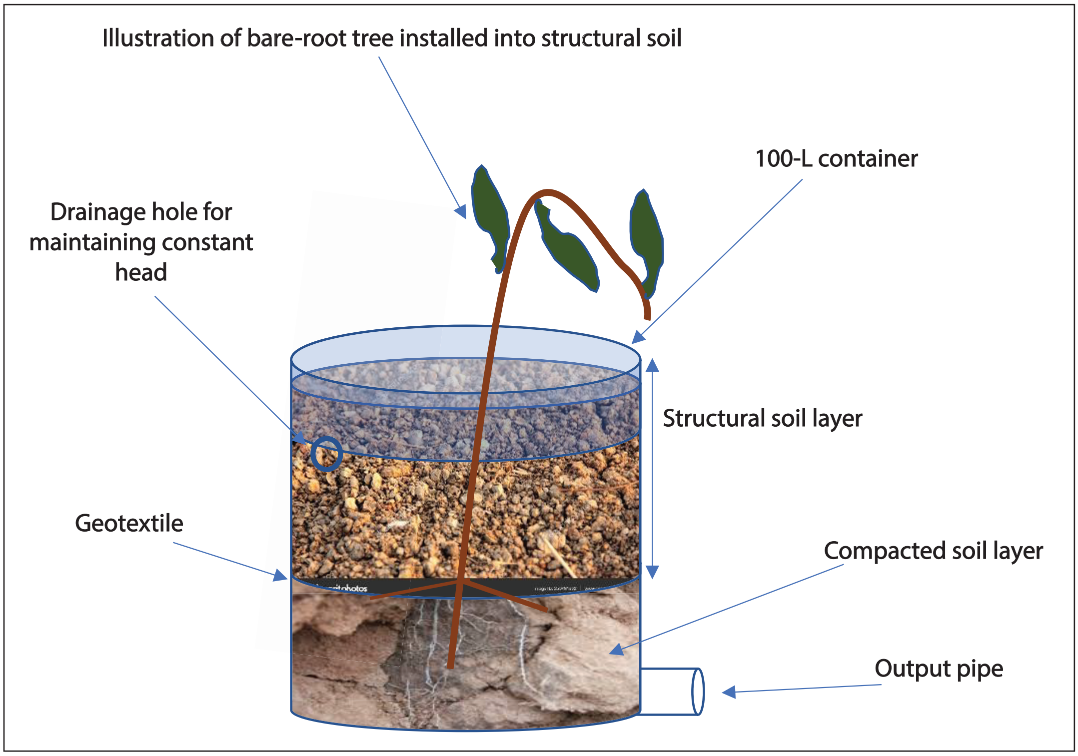


**Figure 2. Schematic illustration of experimental set-up for Experiment 2: structural soil study (not to scale).**

Structural soil was separated from compacted soil using geotextile. The containers were used to simulate a stormwater reservoir (Figure 2). The compacted soil was comprised of 12% sand, 35% silt, and 53% clay. The compacted soil was made from 3 lifts of soil; each lift had 18 kg of soil (dry weight: 10.3 kg) that was compacted with 18 strikes using the same equipment and methodology applied in Experiment 1 to achieve a bulk density of 1.66 g $cm^{-3}$. Thereafter, structural soil filled the rest of the container with bare root *Pouteria obovata* and *Calophyllum soulattri* ($n = 9$) installed alongside the preparation of structural soil in the containers. The mix for structural soil was a gravimetric percentage of 80% granular crushed stone (2 cm to 4 cm in diameter) and 20% soil (clay loam), much like the CU-soil described in Grabosky and Bassuk (1998). The pH was at 5.5, and organic matter averaged at 5%. As with the compacted soil layer, compaction for structural soil was achieved through 18 strikes using the same equipment and methodology applied in Experiment 1. All containers (those with trees and those without) were irrigated until the soil was unable to absorb any additional supply of water, and this was applied daily. A circular piece of geotextile was placed between the compacted and structural soil layers. Containers were placed above a drain to function as water collection.

### Hydraulic Conductivity

Although the experimental duration was 1 year, the trees were installed and left to grow for 4 months prior to the measurement of saturated hydraulic conductivity ($K_{sat}$). The containers were saturated with water until the point where excess water started emerging out of the drainage hole at the top of the container. Volumetric water that accumulated in the output pipe (Figure 2) within a minute was measured while a constant supply of water was provided via irrigation sprays. This was repeated twice for every container, and a mean was taken as the final measurement. To obtain the harmonic mean of $K_{sat}$, we had assumed that there was no hydraulic loss within the structural soil layer due to its high permeability, and observations on harvest indicated that the geotextile was also not clogged. $K_{sat}$ was calculated as follows:

$$K_{sat} = (L \times Q) / (\Delta H \times A)$$

where $L$ = the height of the soil, $Q$ = the volumetric flow rate, $\Delta H$ = the distance of the top drain hole from the base of the pot, and $A$ = the average cross-sectional area of the soil.

To facilitate comparisons between Experiment 1 and the structural soil study, the $K_{sat}$ was determined as in Bartens et al. (2008) with some modification. The modification is an assumption based on an open field scenario, which is different from the conditions of the container experiments undertaken here. In this modification, a limiting steady-state flow model was used, which accounts for soil extending in all directions away from a hole that was augered. This assumption is consistent with the flow of water that tends to move across the soil profile and out via the drainage holes, as in the container experiments used here.

### Root Measurement

Soil beneath the geotextile was removed during harvesting. Thereafter, roots that penetrated the geotextile that were larger than 2 mm (diameter) measured using a caliper were accounted for and their diameters recorded. All roots that penetrated the geotextile and grew into the compacted soil were removed, subjected to oven drying at 80 °C, and subsequently their weights recorded. Additionally, observations were also recorded for the depth of the deepest root alongside roots that were found growing down the sides of the container.

## Analyses

ANOVA was used to analyse all experimental data following the GLM procedure using SAS (SAS version 9.3; SAS Institute, NC, USA). Root count means and variances for Experiment 1 were not independent, so the means were transformed using their square root before statistical analyses were made. This additional step was necessary, as the data was not normally distributed.

# RESULTS

## Hydraulic Conductivity for Experiment 1

There was evidence to suggest that the presence of *Pouteria obovata* and *Calophyllum soulattri* trees benefited hydraulic conductivity as opposed to containers that had no trees (Figure 3a and 3b). The increase in hydraulic conductivity was significantly higher for *Pouteria obovata* as opposed to *Calophyllum soulattri* (Table 1a and 1b). A clear trend was observed for the increase in hydraulic conductivity across the

**Table 1a. Experiment 1: Contrast *P*-values determined using PDIFF, GLM procedure (SAS) for hydraulic conductivity of *Pouteria obovata* and *Calophyllum soulattri* through 2 levels of soil compaction—1.45 g $cm^{-3}$ and 1.66 g $cm^{-3}$—across 6 measurement dates in a year.**

| Compaction level 1 (dry density = 1.45 g $cm^{-3}$) | Contrast *P*-values | | | | | |
|---|---|---|---|---|---|---|
| | 10 Feb | 15 Apr | 12 Jun | 13 Aug | 10 Oct | 15 Dec |
| *Pouteria obovata* vs. no tree | 0.002 | 0.015 | 0.001 | 0.001 | 0.014 | 0.006 |
| *Calophyllum soulattri* vs. no tree | 0.004 | 0.023 | 0.27 | 0.023 | 0.023 | 0.142 |
| *Pouteria obovata* vs. *Calophyllum soulattri* | 0.016 | 0.134 | 0.157 | 0.067 | 0.129 | 0.09 |

**Table 1b.**

| Compaction level 2 (dry density = 1.66 g $cm^{-3}$) | Contrast *P*-values | | | | | |
|---|---|---|---|---|---|---|
| | 10 Feb | 15 Apr | 12 Jun | 13 Aug | 10 Oct | 15 Dec |
| *Pouteria obovata* vs. no tree | 0.093 | 0.005 | 0.03 | 0.132 | 0.08 | 0.03 |
| *Calophyllum soulattri* vs. no tree | 0.143 | 0.105 | 0.07 | 0.213 | 0.105 | 0.215 |
| *Pouteria obovata* vs. *Calophyllum soulattri* | 0.02 | 0.202 | 0.135 | 0.004 | 0.137 | 0.089 |

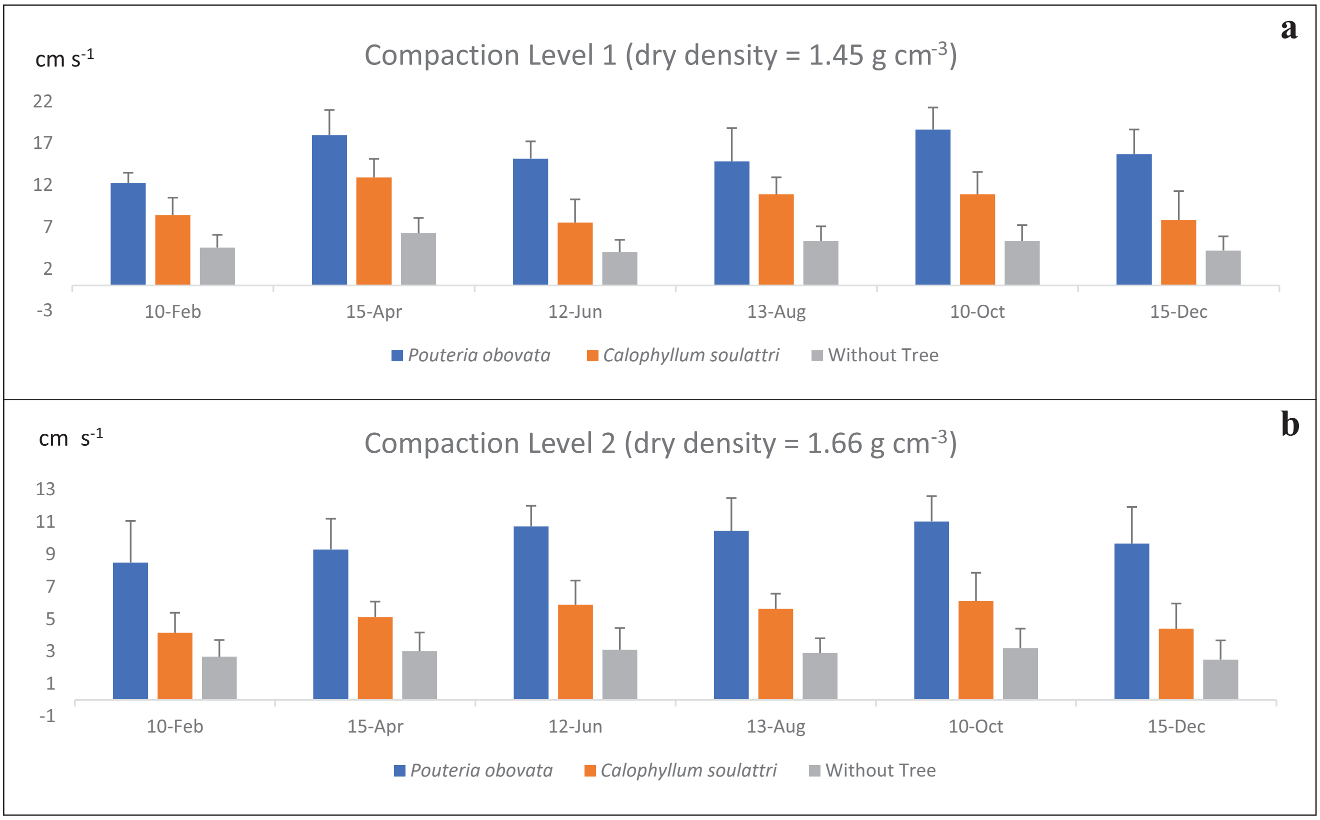


**Figure 3. Experiment 1: Mean hydraulic conductivity through 2 levels of soil compaction—dry densities (a) 1.45 g $cm^{-3}$ and (b) 1.66 g $cm^{-3}$ —across 6 measurement dates in a year for *Pouteria obovata* and *Calophyllum soulattri*.**

12-month period for both levels of compaction. For compaction level 1.45 g $cm^{-3}$, it was found that the benefit to $K_{sat}$ was 33.3% greater for the woody species of *Pouteria obovata* as opposed to *Calophyllum soulattri*. Conversely, a 50% difference was observed for $K_{sat}$ when the comparison was made between *Pouteria obovata* and containers that had no trees. For compaction level 1.66 g $cm^{-3}$, woody tree roots from *Pouteria obovata* benefited $K_{sat}$ by some 34%, which was similar to what was observed at the lower compaction level. Likewise, a similar trend was observed between *Pouteria obovata* and containers that had no trees. A 50% decline was observed in $K_{sat}$ when trees and roots were absent from the containers.

Noteworthy also was that there was no increase in $K_{sat}$ observed over the 12-month period for containers that had trees (Figure 3a and 3b). This was despite clear growth improvements observed in the stem and crown (foliage) over the same period. Minimal percent change was observed across the 6 occasions when measurements were made. A variation of 15.6% was observed for *Pouteria obovata* across the 12-month period. Likewise, a difference of 8.2% and 7% was confirmed for *Calophyllum soulattri* and containers without trees, respectively. In fact, the change in $K_{sat}$ rates across the 12-month experimental period was even lower for compaction level 1.66 g $cm^{-3}$. The difference observed was within a range of 3.5% to 9.8%.

Across the 12-month experimental period and for both compaction levels, containers that held *Pouteria obovata*, which had a woody and coarse root system, were found to have higher hydraulic conductivity as compared to *Calophyllum soulattri.* The difference was that the latter tended to develop a fibrous root system. Additionally, there was little variability (Tables 1 and 2) in the data collected which provided strong evidence that the differences in rooting types between the species played a key role in the differences in $K_{sat}$ observed in this study. In addition, the 50% difference in $K_{sat}$ exhibited by containers that had no trees further supports this claim.

### Root Growth Within the Containers

On harvesting, it was confirmed that the roots of both species had penetrated the mulch and grown into the surrounding compacted soil. Few roots were found developing out of the drainage holes, extending some 15 cm to 20 cm from the holes when they did emerge. In addition, there was no evidence to suggest that the different levels of compaction altered root distribution in either species (Figure 4a and 4b, Table 2). The roots monitored for *Pouteria obovata* had a surface area of 33% and 23% for compaction levels 1.45 g $cm^{-3}$ and 1.66 g $cm^{-3}$, respectively. Similar data was observed for *Calophyllum soulattri*, with 37% and 21% for the compaction levels of 1.45 g $cm^{-3}$ and 1.66 g $cm^{-3}$, respectively.

## Experiment 2: Structural Soil Study

### Saturated Hydraulic Conductivity and Root Growth

Saturated hydraulic conductivity ($K_{sat}$) was approximately 50% lower for containers without trees (Figure 5a), which is suggestive of the importance of the presence of trees and more so the root systems for drainage within the containers. On harvesting, it was observed that all trees had roots that penetrated the geotextile and advanced into the compacted soil. On average, *Pouteria obovata* had 8 roots growing through the geotextile and into the compacted soil (data not shown). *Calophyllum soulattri*, on the other hand, had a mean of 4 roots coming through the geotextile

**Table 2. Experiment 1: Contrast *P*-values determined using PDIFF, GLM procedure (SAS) for number of roots per $cm^2$. *P*-values were from roots counted after slicing soil at 2-cm thickness from the bottom and side of containers with *Pouteria obovata* and *Calophyllum soulattri* growing at 2 levels of soil compaction: 1.45 g $cm^{-3}$ and 1.66 g $cm^{-3}$.**

| | Per $cm^2$ surface area root ends | | | |
|---|---|---|---|---|
| | Contrast *P*-values | | | |
| | 2 cm from bottom | 4 cm from bottom | 2 cm from exterior side | 4 cm from exterior side |
| *Pouteria obovata* compaction level 1 vs. 2 | 0.21 | 0.087 | 0.151 | 0.107 |
| *Calophyllum soulattri* compaction level 1 vs. 2 | 0.101 | 0.23 | 0.096 | 0.07 |

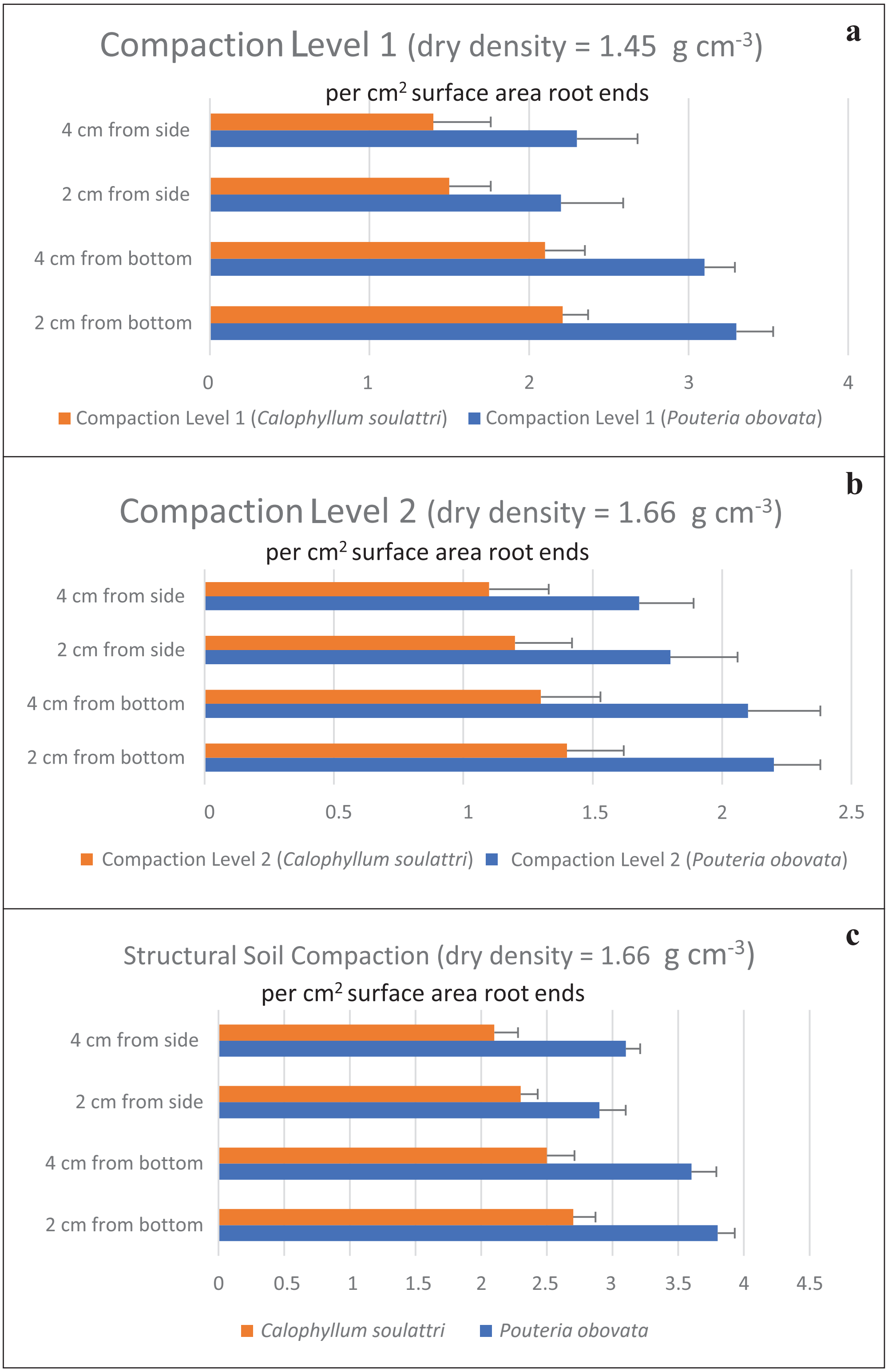


**Figure 4. Experiment 1: Average root counts (cm² surface area) after slicing soil at 2-cm and 4-cm thickness from the bottom and side of the containers, with *Pouteria obovata* and *Calophyllum soulattri* growing at 2 levels of soil compaction: (a) 1.45 g cm$^{-3}$ and (b) 1.66 g cm$^{-3}$. (c) Experiment 2: Average root counts (cm² surface area) for structural soil.**

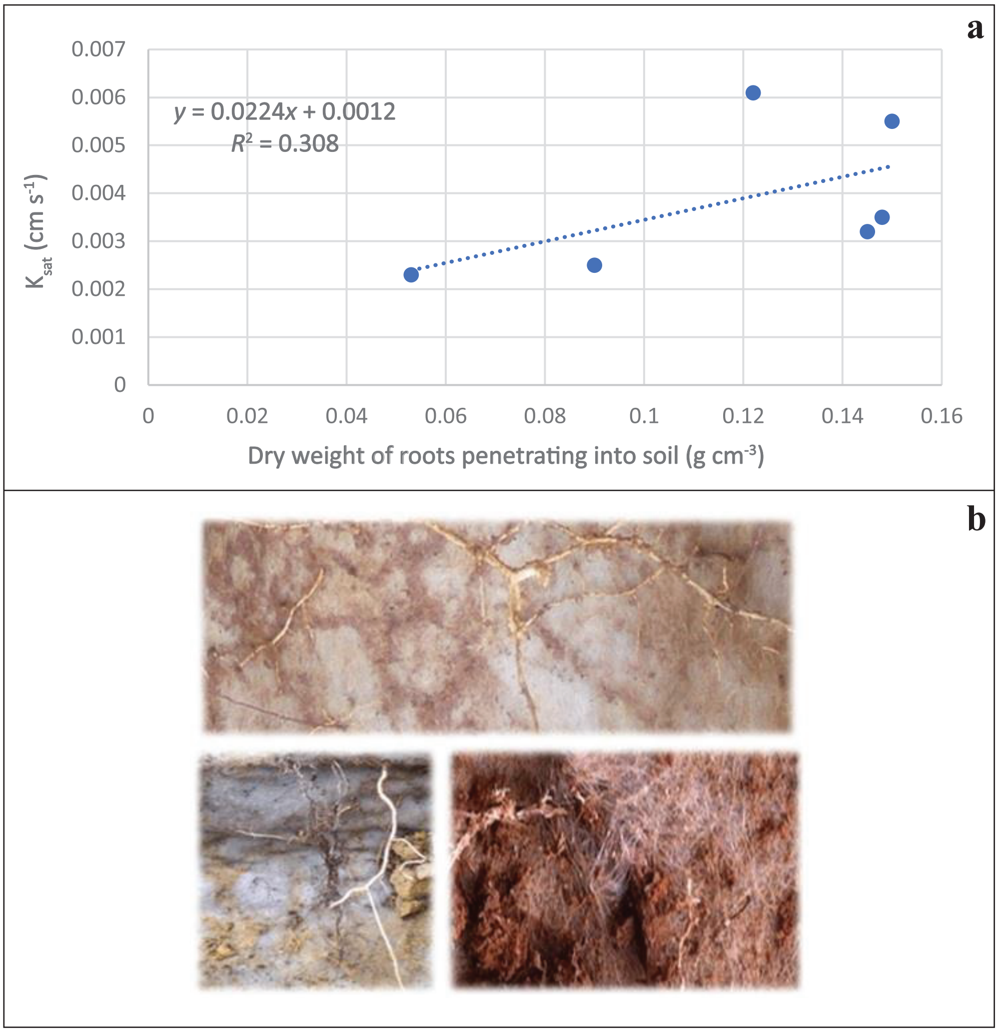


**Figure 5. Experiment 2: (a) Regression analysis (pooled data) of root dry weight as a function of $K_{sat}$ ($y = 0.0224x + 0.0012$, $R^2 = 0.308$); (b) Zoomed-in images showing roots that penetrated geotextile in Experiment 2, where containers with and without trees were installed with structural soil.**

and advancing into the compacted soil (data not shown). In addition, the size of roots that were ≥ 4 mm averaged at 6 and 3 for *Pouteria* and *Calophyllum*, respectively (data not shown). Relationship analysis between $K_{sat}$ as a function of total cross-sectional root area that penetrated the geotextile was weak ($R^2 = 0.203$), but stronger relationships were observed for $K_{sat}$ against the dry weight of roots that penetrated the geotextile ($R^2 = 0.308$)(Figure 5a). Visual observations were suggestive of good root development within the structural soil, which gradually declined as they approached the compacted soil. It was noteworthy that in instances where the geotextile barrier was broken, either during compaction or by stones held within the structural soil layer, roots were found to have developed effectively into the compacted layer (Figure 5b). In addition, there was an absence of roots developing along the sides of the containers, and none at the base of the containers or growing out of drainage holes (unlike Experiment 1).

## DISCUSSION

Urban soils are often disturbed, heterogeneous, and compacted. The soil bulk densities used in this study were within the ranges for urban soils of their textural class. Two tree species were tested for hydraulic conductivity, and both were found to be beneficial when compared with controls that had no trees. Both woody, coarse and fine, fibrous root structures were evaluated for their effects on hydraulic conductivity aided by root penetration.

Experiment 1 and the structural soil study both showed that tree roots can improve hydraulic conductivity in compacted soils. Roots were found to have penetrated compacted soils, but it is important to note that the conditions of the soil were generally moist before measurements. This tended to have implications on soil strength, and root growth would be enhanced for species tolerant of moist conditions. Therefore, the outcomes may vary with tree species dependent on their tolerance of inundation (Ow and Ghosh 2017a). Future research should attempt to understand root colonisation and penetration capabilities in dry soils and in actual field environments across varying species and rooting types (e.g., woody vs. fibrous, etc.). However, it was clear from the data from Experiment 1 that trees with coarse and woody root systems gave rise to higher hydraulic conductivity when compared to those with fibrous roots. By contrast, the comparison between woody roots and controls (without trees) indicated a twofold difference in hydraulic conductivity. In addition, the magnitude of change was similar across both compaction levels. This ran counter to our expectations, as the higher compaction levels were assumed to have affected drainage more extensively given the smaller pore sizes within the soil. This absence of change may reflect the need for a wider selection between bulk densities for differences to show. By contrast, differences were observed in Bartens et al. (2008) in which similar bulk density values were tested. The species and soil types used, however, were different. In addition, a longer experimental duration to facilitate root growth and varying root architecture may also be factors that will impact infiltration through compacted soils (Jin et al. 2017). Although there were some improvements observed in hydraulic conductivity across the 12-month period, the magnitude of improvement was limited. Values ranged between 7% to 13% for the lower level of compaction and approximately 3% to 9 % for the higher level of compaction. The small improvements may partly be explained by the short experimental duration, soil type, and root architecture (Tron et al. 2015; Ow and Ghosh 2017a; Zaibon et al. 2017). Nonetheless, as with hydraulic conductivity, root growth observations (upon harvesting), alongside that of infiltration improvements over time, indicated a strong species effect, whereby the species that possessed woody and coarse root systems exhibited significantly higher hydraulic conductivity. More importantly, such outcomes can provide urban municipalities and urban arborists with informed decisions on species choice when mitigating the ill effects of compacted soils in relation to drainage. Furthermore, the results also provide insights into the importance of an urban forest in highly urbanised cities to mitigate the effects of urban surface runoff that has been exacerbated due to changing climatic conditions (Xiao and McPherson 2003; Armson et al. 2013).

In the trial involving structural soils, $K_{sat}$ for containers without trees was found to be 50% less efficient in drainage. Noteworthy also was that the trees that grew in structural soil were approximately 30% larger than those in Experiment 1 (mean stem diameter and height were 6 cm and 2 m at harvest, respectively). Apart from confirming that all roots had grown through the structural soil and penetrated the geotextile, the number and size of roots in the structural soil study were approximately 12% to 20% greater than those observed in Experiment 1 (Figure 4c). These data, alongside visual observations, were supportive of an ideal growing condition provided by the structural soils for tree roots that facilitated lateral and downward penetration of roots.

The ability for tree roots to penetrate compacted soil and increase hydraulic conductivity will, in turn, reduce surface runoff, enhance groundwater recharge, and improve water quality (Bartens et al. 2008). Similarly, we would expect species adapted to wet and dry soils to grow best in urban stormwater systems with structural soils, given the high porosity rates and reservoir features of these systems (Mullaney et al. 2015). Also important to note is the nutrient content of soils and the depth at which the nutrients are located. For example, Sæbø and Ferrini (2006) and Yang et al. (2014) have recorded that root penetration was reduced when nutrients were located in the top layers of the soil. However, more research into this area will be required to validate these findings.

It is also worth noting that the effect of root development and drainage would also depend on other factors, such as the level of the water table (Imada et al. 2008). Additionally, future work should also focus on the geotextile used in urban stormwater systems. Although the geotextile was found to be in a good condition in this study (e.g., unclogged), such material tends to get blocked over time, and this may impede upon root penetration. The data also indicated the importance of species selection when considering urban stormwater systems. While the construction and design of urban stormwater systems are fundamental, the choice of species should not be neglected. Species adapted to waterlogged conditions are expected to excel in urban stormwater systems. Tolerance for waterlogged conditions can confer abilities to penetrate compacted, saturated soils, since soil strength is reduced under such conditions (Sairam et al. 2008).

## CONCLUSION

Roots penetrated compacted soils, resulting in improved hydraulic conductivity. In the structural soil experiment, roots were found to have penetrated the geotextile. The woody coarse-rooted species, *Pouteria obovata*, improved hydraulic conductivity twofold when compared to the fine-rooted species, *Calophyllum soulattri*. The outcomes of this study, along with previous reports, suggest the importance of vegetation being incorporated within urban stormwater systems to enhance hydraulic conductivity and potentially increasing their capacities to withstand higher volumes of water within a shorter span of time.

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**Résumé.** En règle générale, le ruissellement découlant des précipitations est une cause importante d'inondations et de pollution de l'eau dans les communautés urbaines. Le processus d'implantation de bassins de bio-rétention, bien que long et coûteux, est une approche pour surmonter ces enjeux. Le recours à des sols structurels dans les bassins de bio-rétention, conçus pour recevoir et retenir les eaux pluviales, procure à ces systèmes des fonctions complémentaires permettant de supporter les charges et de faciliter la croissance des racines des arbres et leur exploration du substrat. Les voies créées par les racines des arbres au cours de leur croissance peuvent également faciliter l'écoulement de l'eau dans le profil du sol. Dans cette étude, le potentiel des racines d'arbres à pénétrer les sols compactés et à augmenter les taux de conductivité hydraulique a été examiné en parallèle avec l'utilisation de sols structurels dans le contexte des systèmes d'eaux pluviales urbaines. Pour la première expérience, des plants de *Pouteria obovata* et *Calophyllum soulattri* ainsi qu'un cas témoin (sans arbre) ont été placés dans des manchons de plantation cylindriques entourés de terreau argileux compacté selon deux niveaux de compacité (densités volumique de 1,45 g cm$^{-3}$ et 1,66 g cm$^{-3}$). Les racines des deux espèces ont pénétré dans le sol compacté et la conductivité hydraulique s'en est trouvée augmentée de 50% en moyenne. Dans la seconde expérience, les mêmes espèces ont été cultivées dans un sol structurel alors qu'un géotextile a séparé le sol compacté (densité volumique de 1,66 g cm$^{-3}$) du sol structurel (compacté). Un nombre plus élevé de racines et d'un diamètre plus grand de *Pouteria obovata* ont pénétré dans le géotextile et la conductivité hydraulique a été multipliée par deux par rapport aux cas témoins où aucun arbre n'était présent. La culture de plantes à racines ligneuses et l'installation de sols structurels dans les systèmes de gestion des eaux pluviales urbaines peuvent conférer les avantages pour une meilleure infiltration de l'eau et un meilleur développement des racines ainsi qu'un potentiel d'amélioration globale de la santé des arbres.

**Zusammenfassung.** Typischerweise ist der Oberflächenabfluss von Niederschlagswasser eine der Hauptquellen für Überschwemmungen und Wasserverschmutzung in städtischen Gemeinden. Der kostspielige und zeitaufwändige Prozess der Installation von Bio-Rückhaltebecken ist ein Ansatz zur Bewältigung dieser Herausforderungen. Die Implementierung von Strukturböden in Bio-Rückhaltebecken, die Regenwasser aufnehmen und zurückhalten sollen, verleiht diesen Systemen zusätzliche Funktionen, um Lasten zu tragen und das Wachstum und die Erforschung von Baumwurzeln zu erleichtern. Die Kanäle, die Baumwurzeln während ihres Wachstums bilden, können auch den Wasserfluss im Bodenprofil unterstützen. In dieser Studie wurde das Potenzial von Baumwurzeln, verdichtete Böden zu durchdringen und die hydraulische Leitfähigkeit zu erhöhen, zusammen mit der Verwendung von strukturellem Boden im Zusammenhang mit städtischen Regenwassersystemen untersucht. Für das erste Experiment wurden *Pouteria obovata* und *Calophyllum soulattri* zusammen mit einer Kontrolle (ohne Baum) in zylindrische Pflanzhülsen gesetzt, die von verdichtetem Tonlehm mit zwei Verdichtungsgraden (Schüttdichten von 1,45 g $cm^{-3}$ und 1,66 g $cm^{-3}$) umgeben waren. Die Wurzeln beider Arten durchdrangen den verdichteten Boden, und die hydraulische Leitfähigkeit wurde um durchschnittlich 50% erhöht. Im zweiten Experiment wurden die gleichen Arten in Strukturboden angebaut. Ein Geotextil trennte den verdichteten Boden (Schüttdichte von 1,66 g $cm^{-3}$) vom verdichteten Strukturboden. Eine größere Anzahl von Wurzeln sowie größere Wurzeldurchmesser von *Pouteria obovata* durchdrangen das Geotextil, und die hydraulische Leitfähigkeit wurde im Vergleich zu den Kontrollen ohne Bäume um das Zweifache erhöht. Der Anbau von holzbewurzelnden Pflanzen und die Installation von Strukturböden in städtischen Regenwassersystemen kann Vorteile in Form von erhöhter Wasserinfiltration und verbesserter Wurzelentwicklung mit sich bringen, neben potenziellen allgemeinen Verbesserungen der Baumgesundheit für Regenwasserkontrollsysteme in städtischen Umgebungen.

**Resumen.** Por lo general, la escorrentía de la precipitación superficial es una fuente de inundación y contaminación del agua en las comunidades urbanas y el costoso y lento proceso de instalación de cuencas de biorretención es un enfoque para superar estos desafíos. La implementación de suelos estructurales en cuencas de biorretención diseñadas para recibir y retener aguas pluviales proporciona a estos sistemas funciones adicionales para soportar la carga y facilitar el crecimiento y la exploración de las raíces de los árboles. Los canales que producen las raíces de los árboles a medida que crecen también pueden ayudar en el flujo de agua por el perfil del suelo. En este estudio, se examinó la posibilidad de que las raíces de los árboles penetren en suelos compactados y aumentaran las tasas de conductividad hidráulica junto con el uso de suelo estructural en el contexto de los sistemas urbanos de aguas pluviales. Para el primer experimento, *Pouteria obovata* y *Calophyllum soulattri* junto con un control (sin árbol) se colocaron en contenedores de plantación cilíndricos rodeados de marga de arcilla compactada en dos niveles de compactación (densidades relativas de 1.45 g $cm^{-3}$ y 1.66 g $cm^{-3}$). Las raíces de ambas especies penetraron en el suelo compactado, y la conductividad hidráulica se incrementó en un promedio de 50%. En el segundo experimento, las mismas especies se cultivaron en suelo estructural y un geotextil separó el suelo compactado (densidad relativa de 1.66 g $cm^{-3}$) del suelo estructural (compactado). Un mayor número de raíces, así como diámetros de raíces más grandes de *Pouteria obovata* penetraron el geotextil, y la conductividad hidráulica se mejoró dos veces en comparación con los controles que no tenían árboles. El cultivo de plantas de enraizamiento leñoso y la instalación de suelos estructurales dentro de los sistemas urbanos de aguas pluviales pueden conferir beneficios a la infiltración de agua, aumentar y mejorar el desarrollo de raíces, junto con posibles mejoras generales en la salud de los árboles para los sistemas de control de aguas pluviales en entornos urbanos.