Tree Performance In Load Bearing Paving – Tree Growth, Health, Storm Water Results.

James Urban, FASLA, ISA
Urban Trees + Soils
915 Creek Drive
Annapolis, Maryland 21403 USA
Jimtree123@gmail.com

INTRODUCTION

In the 1980s, professionals began developing methods to improve tree growing conditions under pavement. Since then, many systems have been advanced to provide additional rooting space under hardscapes. Of these systems, two main approaches have emerged. One approach is structural systems in which paving is designed to bridge over loosely compacted soil, either by spanning between structural elements or with engineered structures within the soil and the pavement structure does not rely on soil for support. The second approach includes different types of structural soil, where the soil is designed to allow full compaction to support pavement and vehicular loads.

Suspended pavement systems have been increasingly recognized by research as the most effective approach to urban tree growth in recent years. In the UK, the Tree & Design Action Group (TDAG; 2014) published "Trees in Hardscapes - A Guide for Delivery", a document that describes all available root systems. This document does not make a qualitative statement about the relative effectiveness of the different approaches.

Concept testing to understand tree growth and storm water performance has progressed and a body of research work is beginning to emerge. Research and case studies from the UK, Europe, the US, and Canada are identifying trends and allowing for comparative results and a better understanding of differences.

Other factors impact tree performance such as soil type, how water is brought in and out of the soil, and the quality of nursery stock. The above factors compound to determine if the tree is successful. Other urban stresses such as tree abuse, dramatic weather events, insect invasions, accidents, and lack of or exceptional maintenance impact the success of the tree. Typically, these are not part of controlled research efforts but are factors in case studies that observe trees in urban conditions.

Current research is divided into three general categories. First, controlled studies where compounding stress factors are minimized by growing the trees in a secure research plot. Second, statistical analyses of trees growing in actual streetscapes where stressors are not controlled or predictable but where a range of stress is experienced. And third, institutional reports and summaries of experience that are relevant to understanding performance differences. While the last category is anecdotal, enough trees are now planted in the landscape using these approaches that general observations can support traditional research findings.

LOAD BEARING DEFINED

Each approach is trying to solve the problem of increasing effective soil volume under load bearing pavements in dense urban areas. In this review, it is assumed that usable soils for root growth are limited beyond the treatment zone and that paving must support heavy vehicles. In the United States, a heavy vehicle is generally defined as a AASHTO H20 load which is a 14,500 kg (32,000 LB) axel load. This is standard for a structure that is bridging an unsupported space and applies to suspended pavement. For the two suspended pavement systems discussed in this paper, the stated manufacturer's allowable loading includes the entire assembly of paving, geotextiles, soils within the system, and required compaction under and beside the cells.

For structural soils, the US standard is that subgrade under the paving section must be compacted to 95% of maximum dry density, as measured by a standard proctor test. There are other standards that apply to the type of subgrade material but this report will assume that all structural soil alternatives will meet local load bearing subgrade standards of 95% compaction. In the US, the large truck standard applies to sidewalks (pavements), as trucks and emergency vehicles do often access the sidewalk and cities hope to avoid sidewalk damage.

RELATED FACTORS IN THE EVALUATION OF AN OPTION

While tree growth remains the best way to measure and evaluate soil options, other factors must be considered when evaluating and designing a system. These include:

1. Soil limitations: The soils within systems vary significantly between approaches and result in significant differences in plant response. This factor will be discussed further in the research section.

2. Existing soils: The existing soils that lie under paving outside a treatment zone vary and may contribute to rooting space. It is important for designers to understand existing soil conditions and how they may contribute or detract from tree success. When an approach is successful in the built landscape, it is critical to determine how the existing soils are contributing to rooting space.

3. Water harvesting: Each system depends on water accessing the soil to support the tree: the process of getting water to the tree's roots, and how fast that water drains away are significant to any system's success or failure. Designers must recognize the importance of distributing water throughout the entire soil zone. Reviews of hundreds of water distribution designs indicate that water harvesting distribution is not well executed by the design profession in general (J. Urban, personal experience). Small perforated pipe systems are sold by many companies that bring water to the root ball area only. Very few companies have tackled the obstacle of

extending water distribution under pavement, over the entire soil volume. The City of Toronto's 2013 Tree Planting Solutions in Hard Boulevard Surfaces: Best Practices Manual details solutions to this problem. Since the manual's publication, the city has found that a small trench drain at the backside of the curb, connected into the Silva Cells (not to a drain line), is the most effective way to water soil below pavement. This solution is not shown in the above-mentioned Toronto manual.

4. Layout flexibility: It's critical to consider how difficult it is to work around underground obstructions, including utilities and foundations, when selecting a system. Structural soil systems generally have few layout limitations, while suspended pavements systems are more limited.

5. Maintenance: Maintenance of the system, tree, water harvesting and drainage systems, plus any utilities within and below the system must be discussed during the design process. The organization responsible for maintaining the street or space must understand the system requirements and limitations.

6. Storm water: Effectiveness of the system as a storm water management approach is not a factor in every project, but when it is part of the design intent, the effectiveness of the approach must be considered.

7. Volumetric effectiveness: How does one cubic unit of the material compare to one unit of loam soil. This simple metric must be a factor when selecting one system over another. No two approaches are equal. Ultimately, the pricing of one cubic unit of any material must be compared to how much loam soil, or its equivalent, is being purchased. For example, gravel based structural soil is only about 20% soil by volume. The rest is rock that functions to hold up the sidewalk. One cubic meter of structural soil includes about 0.2 cubic meters of soil and only the soil component should be included in the soil calculation.

Not all systems have been independently researched for the above factors. Personal experience and product claims will need to be considered as part of any evaluation.

OPTIONS CONSIDERD

The following are the most common types of approach in the current market of ideas and will be the focus of this paper. Note that there are many additional options and variations on both structure design and the composition of structural soils than are reviewed. However, the options included herein are considered to represent the range and effectiveness of options currently available. Ideas not discussed here are likely not significantly better or worse than related ideas that are included.

1. Suspended Pavement:
   Silva Cells (post and beam soil cells): A post and deck system developed by DeepRoot Green Infrastructure.

Stratacells (segmented soil cells): A segmented structure developed by CityGreen.

2. Structural Growing Media:
   Gravel Based Structural Soils (GBSS): A mixture of rock and soil with several different formulations and distributors.
   Compacted Sand Structural Soil (CSSS): Sand or loamy sand soil of controlled gradations with several different formulations and distributors.

3. *Arbor Raft* (Hybrid system): A hybrid of suspended paving and sand structural soil developed by Green Tech. Since the majority of tree rooting is dependent on sand/soil underneath the raft part of the system, it will be reviewed as a structural growing media approach.

COMPARATIVE RESEARCH AND ANALYSIS

A total of 26 studies and reports were reviewed and citations are included. Personal experience and observation of built landscapes are also included and noted as "personal experience".

Most current research has focused on tree growth as the determining factor between different systems' effectiveness. When comparing approaches it is important to keep in mind both the properties of the soil used in the system and the system design to support the paving.

SOIL PROPERTIES RESEARCH

The properties of soil used as a rooting medium are just as important to soil under pavement as they are to agricultural farm soil. The original research regarding the ratio of tree size to soil volume uses loam soils as the basis for evaluation. However, current soil volume standards simply refer to "soil" and make no distinction regarding type of soil. Agricultural soil scientist, foresters, and agronomist understand that physical properties of soil significantly impact plant growth. To ignore soil texture, structure, density, chemistry, drainage, and profile in any discussion of how much soil volume to provide for urban trees is to ignore hundreds of years of soil research. Even focusing on soil texture while ignoring something as simple as density can change the entire outcome of a plant's growth.

Recent studies on urban soils consistently find that loam soils with optimum physical properties produce significantly better trees than soils where sand content is very high, to the point of becoming a very sandy loam or a loamy sand (Layman et al., 2016; Fite, et al., 2014; Pregitzer, et al., 2016; Rahman, 2013;Urban et al., 2015). Sand content is a critical distinction as many alternative methods to increase rooting under paving rely on sand, sandy soil, or sandy manufactured soil. In agricultural research, soil with higher levels of silt and clay have higher water holding capacity and higher CEC, creating higher fertility and ability to withstand drought. These heavier soils are an excellent resource for tree growth. The original research regarding structural soil (Grabowski and Bassuk 1995, 1996) determined that clay loam soils, as part of the formula for gravel based structural soil, was critical to the success of the product.

Soil density increase is a significant limitation to root growth. The Watson et al. (2014) review of research papers on soil's influences on root growth cites that even small increases in soil density negatively influences root growth. This must be included in any prediction of tree performance, particularly with approaches that depend on soil as a load bearing material. The more that soil is compacted, the greater the amount of soil volume that is needed. Layman et al. (2016) report the long-term study of the positive effect of loosening soil to improve tree performance.

Soil structure is well documented as a critical property of loam soil in agriculture. Urban et al. (2015) and Layman et al. (2016) demonstrated that preserving soil structure in soil mixes through the elimination of both fine tilling and soil screenings improved tree growth. Preserved structures in these studies included peds (large clumps).

Soil chemistry varies. This review assumes that designers understand soil chemistry sufficiently to adjust to local source limitations, particularly pH. Soil profile and drainage vary from site to site and each approach must accommodate local conditions. Assuring water is getting into the soil is a crucial part of design and is independent from the effectiveness of the approach. However, without addressing these details, the selected approach is not likely to perform as suggested by the research.

SYSTEM DESIGN RESEARCH

Each approach varies significantly in its design. The following is a review of research on both suspended pavement systems and structural soil.

SUSPENDED PAVEMENT SYSTEMS

Sufficient research exists for the following two systems to render them appropriate to include in this paper.

1. Silva Cells (post/deck soil cells): A plastic post and deck system developed by DeepRoot Green Infrastructure. The cells can be filled with a range of soils but function best with unscreened loam soil. The cells may even use the soil that is excavated from the installation site. The system design includes a series of geogrids and geotextiles and a compacted gravel base.

   The large spaces between the cells allow utility lines to easily pass through the soil or for the system to be built around existing lines. The open nature of the structure allows easy soil installation, proper compaction, and verification of the soil installation.

   Individual stacks of cells are structurally independent from one another and spacing between cells can vary, allowing the layout of the system to fill spaces of varied dimensions. This is a critical feature in a complex underground environment where pipes and foundations are common obstructions, or where the cell layout must adapt to the varied dimensions of a streetscape right of way where spacing of objects like trees, streetlights, manholes, and inlets exist.

Maintenance of utilities has been tested. The City Of Toronto has developed a winter utility repair procedure to dig through and repair Silva Cells (Toronto, 2013).

2. Stratacells (segmented soil cells): A segmented structure developed by CityGreen. The structure is based on a triangulated honeycomb frame that interconnects vertically and horizontally to adjacent cell units. Soil is placed into relatively small openings at the top of the cell and vibrated down into the structure after it is built. How much soil actually flows into the complex arrangement of compartments depends on the type of soil, soil moisture, and the degree to which the soil has been screened. Installer reliability is critical as it is possible under fill the cells and there is no way to verify how much soil is installed. The soil cannot be physically compacted and significant soil settlement has been observed. Loam soils can be installed if not overly moist. Clay loam soil and some existing site soils may not be usable.

   The system design includes geotextiles and a compacted base material. The cell units must be structurally interconnected to the adjacent cells. This makes the system unable to allow for small field adjustments in dimensional layout. Small diameter conduits can be threaded along space within the cells but alignments must follow the layout. Utility conduits larger than about 100 mm (4”) diameter must be placed between cells creating gaps in the structure. Repair methods for utilities within or under the interconnected structure is not well documented.

Suspended Pavement Research: Research exists that examines tree performance in constructed landscapes and includes suspended pavement systems (Urban and Smiley, 2014; Urban et al., 2016; Fite, et al., 2014). These studies confirm that trees in suspended pavement systems filled with loam soils were as successful as trees growing in loam soils not under pavement. One study of suspended paving in Boston included healthy 45-year-old trees.

Suspended pavement systems offer the opportunity to install the greatest amount of soil in the smallest space. For projects with the goal of providing sufficient quantities of unscreened soil to support large, mature trees they may be the only option. The high percentage of space within the system (over 90%) maximizes the efficiency of the soil to structure ratio. The TADG manual makes no distinction between various crate options in the market, but the differences in effectiveness are significant (J. Urban, personal experience).

The post system in Silva Cells create large interconnected spaces between columns. Stratacell uses segmented, triangulated structures to create many small spaces separated by the structural walls that support the load. Some of the barriers are perforated but the movements of soil and water from space to space is limited by the size of the perforations. The ability of water to move is limited by capillary forces to pass water through perforations. It is unclear if roots and water use these small spaces as equally available rooting zones.

The difficulty of installing soil into all spaces within Stratacell and compacting it to optimum density is a serious limitation. A 0.85 m^3 (30 ft^3) space created by Stratacell requires filling 109 individual spaces. Compaction of the soil within these spaces is critical. While over compaction can restrict rooting, under compaction of loose soil results in excess settlement and loss of soil volume. The settlement reduces the actual soil volume in the structure and this loss must be factored into the final calculation. In a study comparing Silva Cells to Stratacells, the volume of soil installed into Stratacells was 20% less than the volume of soil installed in the same space created by Silva Cells (Urban et al., 2016). As the study progressed, the soil in the Stratacells settled an average of an additional 3.7 cm (1.46”) while the soil in the Silva Cells only settled 1.57 cm (0.63”). In this same study, the trees in Silva Cells grew slightly better than Stratacells but trunk diameter growth data was not significantly different. The experiment, now in its third growing season, has not been in place long enough to see the impact of volumetric loss due to segmentation in the Stratacells.

Rahman (2013) compared a segmented, interlocking root cell system (an earlier version of the Stratacell) filled with a loam soil, a compacted sand soil, and a control loam soil with normal compaction. The loam soil filled segmented system grew trees at the slowest rate while the loam soil control performed significantly better than both other treatments. The paper’s conclusion suggests that the issue affecting tree growth was the paved soil surface in the tree pit. However, research since shows that covering the soil in the tree pit does not negatively impact trees Urban et al (2014).

Urban et al (2014) observed 408 trees in Silva Cells at 10 built environment projects across the US and Canada and found very strong growth rates and survival: 79% of trees were growing at an average trunk diameter increase of 1.02 cm (0.4”) or greater per year, with 29% growing faster than 2.0 cm (0.8”) per year.

The studies that measured trees in suspended pavement found that those trees often grew slightly faster than the positive controls of similar loam soil with no paving. However, more study is needed before concluding that loam soil under paving is more effective than loam soil in open tree beds.

While both approaches may use loam soil, as the soil becomes wet or contains more clay, the degree of difficulty in filling Stratacell’s small spaces increases.

More research is needed to better quantify the difference between the two approaches. The difference in the amount of soil that can be placed into each system and the resulting difference in settlement may affect the sizing of the two systems. It would seem reasonable to require the volume of Stratacell systems to be 20% larger than Silva Cell systems in order to attain the same soil volume.

STRUCTURAL GROWING MEDIA

Two systems have sufficient research to be included in this paper, gravel based structural soil and compacted sand structural soil. A third system, Arbor Raft, is a hybrid which includes suspended pavement supported by sand. While no specific research into the effectiveness of the Arbor Raft system was found, the research on compacted sand structural soil is applicable. The conceptual differences between gravel based structural soil and compacted sand structural soil is significant enough to warrant a separate discussion of each approach.

Gravel Based Structural Soils (GBSS): A mixture of rock and soil, developed in the mid-1990's. Many formulas have evolved from the original concept development. Grabowski and Bassuk (1995, 1996) found that about a 30% void space exists in standard crushed gravel and if an optimum of 20% clay loam soil was introduced, gravel pieces would still touch each other allowing full compaction of the material. This meets road subgrade standards and the soil remains loose, at close to optimum compaction for root growth. The rocks in the mix were about 1.9 cm (¾") diameter and not particularly angular. The studies observed that using larger stones did not increase the soil volume but that using more angular stone did slightly increase soil volume. As the mix ratio approached 30% rock, the soil in between the stones became more compacted, reducing root growth.

GBSS was first installed in the US around 1996 with initially good tree performance results, but by the early 2000's tree decline was being observed. Loh et al. (2003) showed that a tree would grow well until it reached the limit of the small amount of soil in the matrix and then would begin a decline. In later work, Grabowski and Bassuk (2016) observed that one group of trees was performing similarly to nearby trees in a park, planted in loam soil. But, cracks in the sidewalk were also observed, indicating that the first group of trees' roots were likely growing into the park and making use of its loam soil.

Buehler (2012) observed that lindens in Copenhagen were growing at an average of 0.95 cm (0.37") radial increment per year after 5 years planted in large beds of structural soil and using a much larger rock size (but similar shape to Grabowski et al., 2016). The tree growth was consistent. This is a lower growth rate than observed in suspended pavement studies.

Kristofersen (1999) found that brick or lava, when used as the gravel material, improved the growth results to match the growth rates of the topsoil control. This was only a two-year container experiment where irrigation and fertilizer was added which could have masked the deficiencies found in other structural soil studies.

Fite et al. (2014) found that trees in GBSS significantly underperformed when compared to loam soil suspended pavements.

Urban et al., (2016) observed that trees in aggregate based structural soil grew significantly slower than trees in suspended pavements with loam soil. The study also tested an expanded shale aggregate, somewhat similar to the lava in the Kristofersen study, but found slower growth than the standard gravel used in the GBSS mix.

Urban's personal observations of numerous gravel based structural soil installations in the US indicate that trees generally grow well at first (5 years…), and then slow or decline as they reach the limits of the soil in the stone.

In Stockholm, Sweden a different GBSS approach is used (Stockholm, 2009). There are significant differences between Swedish structural soil and structural soils made with smaller gravel. In addition to a different specification for the structural soil, the Stockholm approach includes many additional requirements that exceed normal tree planting requirements in the UK. These differences are critical and must be both understood and followed if the results are to be similar. The environmental conditions, as well as geology and soils, in Stockholm are different from London. In Stockholm, summer temperatures are slightly cooler and slightly wetter and there are significantly more hours of sunlight. The geology of the area includes a granite rock base and soils that vary from sandy soils to marine clays. The presence of large quantities of granite in Sweden may make replication of their soil approach more expensive in other places.

In Stockholm soils, the aggregate is a much larger size (100-150 mm (4-6") than other GBSS mixes, and a very angular granite. The soil is silt loam with between 25 and 55% silt/clay. Critical to the design is washing the soil into the stone in layers after the stone is compacted. The amount of soil in the mix is approximately 25% of the total volume. The soil is used in very large quantities with a minimum of 15 m^3 for small trees and large beds that may be 30 m^3 or greater for large trees. The minimum bed width for large trees is 4 m with the length extending from tree to tree. Each system is designed with a robust water harvesting system to capture as much water as possible, which then flows into the structural soil. Large concrete bunkers surround each large tree and are filled with additional loam soil to establish the tree. The system is designed to encourage rooting beyond the limits of the treatment zone. Photos of root excavations indicate that roots often grow into soil under and around the treatment zone. The detailing of the construction documents and specifications in the handbook are incredibly precise and reflect different conditions well.

The handbook and presentations by the city indicate good tree performance. Ostberg (2014) observed good tree growth with an average of 1.18 cm (0.46") trunk diameter increase per year when the system included the introduction of rain water, and 0.75 cm (0.29") for trees where stormwater was not included. Multiple species of trees were studied, planted along streets.

Solfjeld (2014) in Norway uses a similar approach to Stockholm and reported good results on several built projects, but slow growth in the controlled study. No data was presented but the photos of trees show several different responses. One of the most difficult problems to solve was washing soil into the stone. In each project they resorted to mixing the soil and stone together and then installing the mixture. Obtaining stones that were of the correct size range also proved challenging.

Werz (2012) examined only water volume effects when replicating Stockholm soil in Minnesota planted in 2011 and did not measure tree growth. However, a site visit in 2015 shows all the trees either with little growth, declining, or dead condition (J. Urban, personal observation).

More research is needed to understand why the Stockholm experience has been so much more successful than other structural soil applications. The question of volumetric efficiency appears to still be a limitation but the approach may be useful in places where existing soils around the tree site are a potential as rooting space. To recreate the success of the trees in Stockholm it will likely be necessary to imitate the whole system and not just the large stone and soil relationship. It may also be necessary to recognize and match the Swedish attention to detail throughout the design and construction process.

Compacted Sand Structural Soil (CSSS): loamy sand soil of controlled gradation. The original compacted sand soil concept was developed in Amsterdam in the 1990's (Couenberg, 1994). This soil design is well researched, is used extensively, and performs well with city trees. However, the original design was never intended to be used as a load bearing soil. The soil is only compacted to about 70-80% standard proctor and significant settlement of sidewalks, up to 1.9 cm (¾"), was observed. Couenberg was quite clear that compaction would slow root grow at 85% and would stop root growth at over about 90% proctor (Couenberg - personal communication).

Kristoffersen, (1999) observed that fully compacted sand soil, similar to Amsterdam soil, performed about the same as a compacted subsoil control.

At some point, the idea of CSSS spread to the US and the UK and proponents began to compact it as a load bearing soil. There are many variations of the soil mix design but essentially all are loamy sand or sand textures with tightly controlled particle sizes and added soil and compost (J. Urban, personal observations).

Rahman (2013) found that a loam soil control performed significantly better than a compacted sand soil.

Urban et al (2014) observed 330 trees in various conditions, with the majority in compacted sand structural soil, and found that trees in the sand soils were significantly underperforming relative to trees in open loam soil or loam soil under suspended pavements.

Arbor Raft (Hybrid system): Hybrid of suspended paving over compacted sand structural soil, developed by Green Tech. This is listed in the TDAG document as a crate system (suspended pavement), however it is listed as a sand soil system in this report. The approach typically includes two parts. The first is a plastic sand soil filled layer, wrapped on all sides with a geotextile. The plastic is supported by a sand soil that is compacted to load bearing levels. While the plastic structure is strong enough to resist a significant load while resting on a supporting base, it is not strong enough to span a large enough area of loose material to provide the required soil volume for large trees.

Research was not found related to the success of trees in this system nor was any information regarding the load bearing capacity of the overall assembly. The soil within the plastic crate, enclosed in geotextile, will not allow roots to migrate down to lower levels, a critical component in the design of soil below pavement systems. Without data on the compaction of the sand, it is not possible to evaluate a system/tree relationship. But, if the sand is compacted to above 90%, which it would be for this be a load bearing approach, trees are likely to underperform similarly to other compacted sand designs. If the sand soil is not compacted, then the system is not a load bearing approach.

TREES AND STORM WATER

Using trees and their soil to improve storm water runoff and pollutant removal is a significant goal in many urban tree plantings. However, do each of the soils below pavement ideas work the same? The answer is dependent on the design, how the water is conducted into and out of the soil and the type of soil used. As stated before, designers are currently not doing a very good job of designing the water systems.

The water treatment goals must be clearly defined. These generally are to slow the runoff flow, and/or reduce the overall runoff. Pollutant removal is also critical but may not be required.

Hunt et al. (2012) provides an excellent review of these issues. Optimizing for one goal may conflict with the design needed for another. The recommended comprehensive design to balance all goals uses soil media that drains at 0.007-0.014 mm/s (1-2"/hr), 1.2 m (4') deep. Much slower and much deeper than most systems.

McLaughlin et al. (2014) found that by deep fracturing (preserving soil peds or clumps) in compacted clay loam soils to a depth of 60 cm (24") the soil would absorb over 90% of a 6 cm (2.5") rain event. The 6-year study found the absorption rate remained constant and the soil with roots growing in it did not re-compact.

Page et al. (2014) studying bio-retention soils in Silva Cells found that pollutant removal far exceeded rates of pollutant removal in the average of multiple studies of bio-retention beds.

Rothwell (2016) study of loam soils in Silva Cells found acceptable reduction in runoff time and excellent tree establishment. Turbidity and nutrient data to be released in 2017.

Xiao and McPherson (2008) tested gravel based structural soils for pollutant removal and found that the material quickly became saturated with pollutants and removal rates dropped. The percentage of removal from water with high pollutant loads was very low. The soils had high hydraulic conductivity: 58.4 cm/hr (29”/hr). This caused the volumetric water content to drop from saturated to field capacity in less than 2 hours with 90% of the water-loss in the first 10 minutes, which eliminates the runoff benefit.

Wenz (2012) study of Stockholm soil approach in Minnesota controlled runoff time using a flow control device. Nutrient reduction data were not collected. Trees were slow to establish, declining or dead after 4 growing seasons (J. Urban – personal observation).

Runoff studies and nutrient removal studies were not located for compacted sand structural soil.

CONCLUSIONS

Based on the above, conclusions on volumetric effectiveness of the five approaches reviewed can be proposed:

Soil properties

1. Loam soils that retain large clumps and residual soil peds installed with optimum compaction and drainage are most suited for tree growth.
2. Increasing sand and/or rock in soil reduces tree growth rates by decreasing water holding capacity and reducing soil volume.
3. Increasing compaction above about 85-90% of maximum density per Standard Proctor test reduces tree growth rates.
4. Loam soil can be considered as 100% effective as the standard to evaluate tree performance of other soil options and systems.

Soil volume

1. Published soil volume to tree growth rates are based on loam soils. Substitution of lower quality soils will require greater amount of soil to compensate for the decrease in quality.

System effectiveness

1. Suspended pavement systems that are filled with unscreened loam soils are the most effective at growing trees and are equivalent to loam soil provided that the volume of the structural elements holding up the sidewalk are subtracted from the overall volume of the installation. Silva cells are 7% structure and Stratacells are 6% structure. Unscreened loam soil, is difficult to place into Stratacells completely (19% less than Silva Cells). Silva cell soil effectiveness is 93%; Stratacell soil effectiveness is 75%.
2. Compacted sand structural soil is the most difficult approach to evaluate for efficiency due to limited studies. There are however enough examples of trees growing slowly to consider it as a viable option. Urban et al. (2016) found the trees after two growing seasons increased at half the rate of Silva Cells. More research is needed, but it may be reasonable to rank this option at between 30 to 50% effectiveness compared to loam soil with trees never growing as fast, no matter how much soil is provided.

3. With loam soil included in the formula for gravel based structural soils, the effective amount of soil is between 20 and 25%. Trees can be expected to grow at reasonable rates until the roots fill the available soil space. More research is needed to determine if the soil to tree growth ratio is somehow different for this approach in Stockholm soil.
4. The arbor raft system should not be considered a load bearing approach.
5. For each approach, improving water harvesting will improve the effectiveness. But the improvement in effectiveness should be about the same in each approach.

Design improvements

1. Designers must pay more attention to all the parts of the 'tree in pavement problem' at the design stage. The choice of a soil approach is only one small part of a complex design problem. The best thing a designer can do is to make the hole in the pavement much larger and better understand water harvesting design. Designers must reject the notion that paving right up to the base of a tree and using tree grates is a reasonable design choice!

REFERENCES

Buehler, O. (2012). Root development in rodvenlig fixing (large rock structural soil), trees growing under and above ground level on Kongens Nytorv University of Copenhagen, Conference on Structural Soils. Available at: http://ign.ku.dk/efteruddannelse-kurser/kurser-temadage-og-konferencer/afholdte-konferencer/2014/structural-soils-urban-trees/ (accessed March 2017).

Couenberg, E. (1994). Amsterdam Tree Soil. Watson, G. and Neely, D. (ed.) Proceedings of the First Landscape Below Ground Workshop. International Society of Arboriculture Press, Champaign, IL, USA, pp 24-33.

Fite, K., Kramer, E., Scharenbroch, B., Uhlig, R. (2014). Beyond the Great Debate: Assessing Post Installation Manufactured Soils Performance. Presentation ASLA Annual Meeting, Denver, CO, USA.

Grabowski, J., Bassuk, N. (1995). A New Urban Tree Soil to Safely Increase Rooting Volumes Under Sidewalks. Journal of Arboriculture, 21(1), 187-201

Grabowski, J., Bassuk, N. (1996). Testing of Structural Urban Tree Soil Materials for Use Under Pavement to Increase Street Tree Rooting Volumes. Journal of Arboriculture, 22(6), 255-263.

Grabowski, J., Bassuk, N. (2016). Seventeen Years' Growth of Street Trees in Structural Soil Compared with a Tree Lawn in New York City. Urban Forestry & Urban Greening 16103-109.

Hunt, W., Davis, A., Traver, R. (2012). Meeting Hydrology and Water Quality Goals through Targeted Bio-retention Design. Journal of Environmental Engineering, 138, 698-707.

Kristofersen, P. (1999). Growing trees in road foundation materials. Arboricultural Journal. 23(00), 57-79.

Layman, R., Day, S., Mitchell, X., Chen, D. Y., Harris, R., Daniels, W. (2016). Below Ground Matters: Urban soil rehabilitation increases tree canopy and speeds establishment. Urban Forestry & Urban Greening, 16, 25-35.

Loh, F., Grabowski, J., Bassuk, N. (2003). Growth response of Ficus benjamina to limited soil volume and soil dilution in a skeletal soil container study. Urban Forest & Urban Greening, 2, 53-62.

McLaughlin, R., Kays, B., Mohammadshirazi, F., Brown V. (2014). Controlling Storm Water Quality by Amending Soils for Enhanced Infiltration on Construction Sites in North Carolina – Final Report. Clean Water Management Trust Fund. April 28, 2014.

Ostberg, J. (2014). Structural soils as storm water magazines – Hornsgatan in Stockholm. University of Copenhagen, Conference on Structural Soils. Available at: http://ign.ku.dk/efteruddannelse-kurser/kurser-temadage-og-konferencer/afholdte-konferencer/2014/structural-soils-urban-trees/ (accessed March 2017).

Page, J.L., Winston, R.J., Mayes, D.B., Perrin, C., Hunt, W.F. (2014). Retrofitting residential streets with storm water control measures for water quality improvement at the catchment-scale. Journal of Environmental Engineering, 141 (4) 14-76.

Pregitzer, C., Sonti, N., Hallet, R. (2016). Variability in Urban Soils Influences the Health and Growth of Native Tree Seedlings. Ecological Restoration, 34(2), 106-116.

Rahman, M. A. (2013). Effect of pit design and soil composition on Performance of Pyrus calleryana Street Trees in the Establishment Period. Arboriculture & Urban Forestry, 39(6), 256-266.

Rothwell, J. (2016). Howard St Project – Silva cell rainwater storage project on a flood prone residential street. Initial report, Manchester University.

Solfjeld, I (2014). Structural soil research and examples from Norway. University of Copenhagen, Conference on Structural Soils. Available at: http://ign.ku.dk/efteruddannelse-kurser/kurser-temadage-og-konferencer/afholdte-konferencer/2014/structural-soils-urban-trees/ (accessed March 2017).

Stockholm. (2009). Sweden. Planting Beds in the City of Stockholm – A Handbook. Available at: planting beds in the city of Stockholm a handbook 2009.02.23 gh100322 (accessed March 2017).

TDAG. (2014). Trees in Hard Landscapes – A Guide for Delivery. Trees and Design Action Group. www.tdag.org

Toronto. (2013). On, Canada. Tree Planting Solutions in Hard Boulevard Surfaces, Best Practices Manual. Available at: https://www1.toronto.ca/city_of_toronto/parks_forestry__recreation/urban_forestry/files/pdf/TreePlantingSolutions_BestPracticesManual.pdf
(accessed March 2017).

Urban, J. Marritz, L. (2014). Silva Cell Research Parts 1, 2, and 3. Deeproot web site available at: http://www.deeproot.com/blog/blog-entries/category/research/page/2 (accessed June 2018).

Urban, J., Smiley, T. (2014). Evaluation of Established Trees – Structural Soils and suspended pavement. Presentation at the International Society of Arboriculture Conference Milwaukee, WI, USA.

Urban, J., Scharenbroch, B., Curry, M. (2015). Soil or Sand for Planting: Research and the Soil Debate Continued; Presentation ASLA Annual Meeting, Chicago, IL, USA.

Urban, J., Smiley, T., Roche J. (2016). Will the trees grow? Research and Experience with Soils Below Pavements. Presentation ASLA Annual Meeting, New Orleans, LA, USA.

Watson, G., Hewitt, A., Custic, M., Lo, M. (2014). The Management of Tree Root Systems in Urban and Suburban Settings: A review of Soil Influence on Root Growth. Arboriculture & Urban Forestry, 40(4), 193-217.

Wenz, E. (2012). Structural Soils for Storm Water. Green Infrastructure for Clean Water. Minnesota Landscape Arboretum. Available at: http://www.arboretum.umn.edu/UserFiles/File/2012%20Clean%20Water%20Summit/CWS2012%20Erin%20Wenz%20presentation.pdf
(accessed March 2017).

Xiao, Q., McPherson, G. (2008). Urban Runoff Pollutants Removal of Three Engineered Soils. USDA Forest Service, Center for Forest Research/UC Davis Land, Air & Water Resources, Davis CA, USA.