Comparison of Soil Treatments Under Concrete Pavement

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Abstract

In urban areas there is a limited amount of soil space available for tree root growth, but many systems have been developed to provide rooting space for trees. Of these, two main approaches have emerged: 1) supported pavement and 2) structural growing media. This research is composed of two controlled studies that compare variation of these two approaches. The first was a 10 year study using elm trees that compared gravel based structural soil (GBSS), expanded slate structural soil (ESSS), expanded slate alone, a concrete supported pavement and a compacted control. The second was a four year study using *Liriodendron* trees that compared GBSS, sand based structural soil (SBSS), Silva Cells ™, Stratacells™, an open control and a compacted control. The results of these two studies showed that the trees growing in the supported pavement treatments with low density soil media below had significantly greater growth and generally appeared healthier, and the treatments with the highly compacted soil media had less root development and less top growth. However, soil media that were highly compacted experienced less subsidence.

Introduction

In the 1980s, professionals began developing methods to improve tree root growth under load bearing pavement. Since then, many systems have been advanced to provide additional rooting space for trees. Of these, two main approaches have emerged: 1) supported/suspended pavement and 2) structural growing media. Supported pavements are structural systems designed to support vehicles that bridge lightly compacted soil. Structural growing media are soil mixes designed to be fully compacted to support vehicles and still allow tree root growth (Grabosky and Bassuk, 1995, Smiley et.al. 2006, Urban and Smiley, 2014).

Combining load carrying capacity with tree root growth is challenging since even a small increase in soil density can negatively influence root growth (Alameda and Villar, 2009, Watson et.al. 2014, Layman et.al. 2016). The "Cornell Mix" , a mixture of rock and soil, was the first Gravel Based Structural Soil (GBSS) structural growing media (Grabosky and Bassuk, 1995 and 1996). Grabosky and Bassuk (1995) found that there is about 30% void space in 1.9 cm diameter crushed gravel, and if 20% clay loam soil was mixed with gravel, the larger diameter rocks would still touch and allow for full compaction of the material. This meets road subgrade standards and the soil remains loose, at nearly optimal compaction for root growth. Others have looked at modification to this system by varying the size of the stone in the mix and the percentage of soil in the mix (Stockholm 2009, Wenz, 2012, Ostberg, 2014, Solfjeld, 2014). Studies have found that using larger stones did not increase the soil volume. As the mix ratio approached 30% soil, the soil in between the stones became more compacted, reducing root growth (Urban, 2008).

GBSS was first installed in the US around 1996 with initial good tree performance results, but by the early 2000s tree decline was being observed and limitations were recognized (Grabosky et.al. 2002, Smiley et al. 2006, Fite et.al., 2014, Urban and Smiley, 2016, Grabosky and Bassuk 2016). Loh et. al (2003) showed that a tree would grow well until it reached the limits of water and nutrients contained within a small amount of soil and then would begin a decline. In later work, Grabosky and Bassuk (2016) observed that one group of trees was performing similarly to nearby trees in a park, planted in loam soil (authors' personal observation). This observation led to our hypothesis that the tree roots in this and other studies may have used the structural soil as an "escape path" to a more favorable rooting environment, complicating interpretations from them.

Another structural growing media is the Sand Based Structural Soil (SBSS). This is a loamy sand of controlled gradation (Robert Pine personal communication) and was originally developed for the city of Amsterdam (Couenberg, 1994). However, it was only intended to be compacted to 70-80% Proctor and was never intended to be used as a load bearing soil (Couenberg - personal communication). Most tree root growth is inhibited by soils at 85% Proctor and tree root growth is impeded at roughly 90% Proctor (Urban, 2008)

Variations of the SBSS design have been developed and installed in many landscapes, but our research group and others have begun to notice issues with these plantings over the last decade. In 2013, we noticed trees in the SBSS significantly underperforming trees in open loam soil as well as trees in loam soil in nearby supported pavement plantings (authors' personal observation). Published reports support our observations: Kristoffersen (1999) observed that fully compacted sand soil, similar to Amsterdam soil, performed about the same as a compacted subsoil and Rahman (2013) found that a non-compacted loam soil performed significantly better than compacted sand soil.

Supported pavement systems were first used in the United States in the early 1980's (authors' personal observation). In these systems, the pavement is supported by concrete posts or concrete ledges along the side of the planting area. Since then, several plastic support systems have been developed and commercialized. The concept is to support the pavement so that lightly compacted soil can be installed in the space beneath the pavement. Since the soil is not heavily compacted, root growth impediment is minimized.

With limited and defined soil volume, consideration needs to be given to the amount of soil available in the space. GBSS provide about 20% of the volume for soil and supported pavement systems provide about 90% of the volume (DeepRoot – Silva Cell product literature). Ultimately, if the goal is to provide an escape path for the roots, soil volume is of little important.

The goal of this research was to compare the growth of trees in different supported pavements and structural growing media.

Materials and Methods

We established two plots the Bartlett Tree Research Laboratory in Charlotte, North Carolina, U.S.A. Charlotte has a temperate climate with on average 1118 mm of rain per year. Summers are hot (average July high temperature is 32 °C) and humid, winters are cold (January average low temperature is -0.6 °C).

Study 1

The first plot was installed in 2004, in it each tree was provided a space that was 0.6 m deep and 3 m square resulting in 5.4 cubic meters of available root space.   Root escape was limited by surrounding the growing area with a combination of Biobarrier ™ around the sides and Typar™ 3301 geotextile below (Berry Global, Old Hickory TN). Below the growing area, a 15 cm layer of #57 stone and a perforated drain line run to an outfall.

Treatments were as follows:

1. Gravel based structural soil (GBSS)—comprised of 80% gravel 2.5 to 3.5 cm diameter and 20% sandy clay loam soil. A hydrogel was sprayed on the gravel before mixing with soil. The mix was installed in 20 cm thick layers and were compacted with an impact compactor to 95% Proctor.
2. Expanded slate structural soil (ESSS)—comprised of 80% expanded slate (Carolina Stalite, Salisbury, NC) 1.5 to 2 cm diameter mixed with 20% sandy clay loam. The expanded slate was wetted before mixing with soil. Soil were installed in 30 cm layers and compacted with a vibratory plate compactor to 95% Proctor.
3. Expanded slate alone was installed in 30 cm lifts and compacted with a vibratory plate compactor to 95% Proctor.
4. Supported pavement – Native sandy clay loam was de-compacted using a backhoe excavator after tree planting using the method proposed by Rolf (1994). Concrete posts were installed at the corner to support the concrete pavement that was installed at the soil surface.
5. Compacted Control (CC)—native sandy clay loam was installed in 20 cm layers and compacted with an impact compactor to 95% Proctor.

With the exception of the supported pavement treatment, each treatment was randomly assigned within a row, creating a randomized block design. As a result of the different construction techniques used in the supported pavement treatment, all of these treatments were located in a single row. Concrete was installed over the plots with an 80 cm diameter opening centered on each tree trunk

In each 6 m square treatment, two trees of two different species were planted for a total of four trees per treatment, blocked by rows and replicated three times for a total of 60 trees.

The trees were Snowgoose cherry (*Prunus serrulata* 'Snowgoose') and Bosque lacebark elm (*Ulmus parvifolia* 'Bosque'). These species were selected because they are medium-sized at maturity and root aggressively. Tree caliper measured at 15 cm above soil grade averaged 3.8 cm when installed. Wire baskets and burlap were removed from the top of the root balls at planting. The cherry suffered high mortality rates in some treatments in 2007 and were all removed that year. Cherries were replaced with *Magnolia grandiflora* "Little Gem". Data from the cherries and magnolias are not presented in this paper.

Elm growth (height, spread, and trunk diameter) and color (visual rating and SPAD meter) was evaluated over a ten year period. Tree growth was measured annually at the end of the growing season. Measurements collected were caliper at 15 cm above grade, tree height and crown spread. Foliage color was rated periodically using a visual assessment, and annually with a SPAD 502 chlorophyll meter (Spectrum Technologies, Aurora, IL).

The number of cracksin the concrete surrounding the tree opening thought to be associated with tree roots were counted in 2013.

Study 2.

The second study was installed in 2014. Here smaller plots were used and smaller trees were installed. Each plot was separated from the adjacent plot and the undisturbed soil alongside the trench and with plywood walls on four sides that were 0.5 m deep and 1.5 m long resulting in a 1.1 m^3 of rooting space. The plots were lined with a continuous sheet of Typar ™ 3301 geotextile fabric (Berry Global, Old Hickory TN) to restrict roots from escaping the plots while allowing water drainage. Below the growing area, a 15 cm layer of #57 stone and a perforated drain line run to an outfall.

Treatments were applied to six replicates as follows:

1) Open Control - the sandy clay loam soil excavated from the trench was put back into the plot. Soil was compacted only by people walking across the soil surface to approximately 80% Proctor.
2) Compacted control (CC) - The excavated soil was put back into the plots in 20 cm lifts and compacted to 95% Proctor.
3) Silva Cells- The modular post and deck Silva Cell (DeepRoot Green Infrastructure LLC, San Francisco CA) structure was constructed in each plot by a representative of the manufacturer. Since the dimensions of the plot were not identical to the size of the Stratacell, so the Silva Cells were cut into sections that filled the space (Figure 1). Parts of three Silva Cells were installed in each plot. The soil excavated from the trench was

installed within the plot structure. It was compacted only by human weight to approximately 80% Proctor.

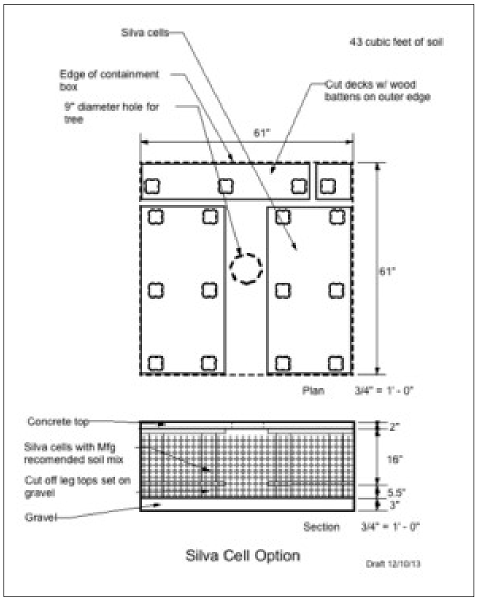

Figure 1. The installation plan drawing for Silva Cells.

4) Stratacells - The modular structure of Stratacell (Citygreen, Sydney, NSW Australia) was installed by a representative of the manufacturer. Sixteen Stratacells were installed in each plot (Figure 2). The excavated soil was installed within the Stratacell structure. The soil was not compacted.

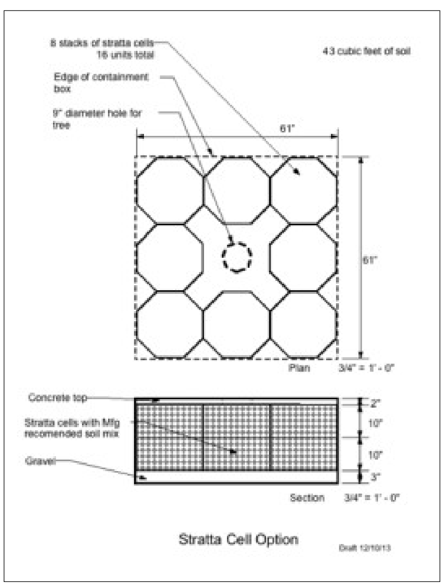

Figure 2. Installation plan drawing for Stratacells.

5) Sand Based Structural Soil (SBSS) – A 5 cm layer of gravel (#57 stone) was installed at the base of the plot above the geotextile. On top of this, a uniformly blended mixture of sand, sandy clay loam, and compost with a ratio of 4S:1L:1.5C was installed in 20 cm lifts and compacted to 95% Proctor (Pine and Swallow Environmental, Groton MA).
6) Gravel Based Structural Soil (GBSS) – A #57 gravel was sprayed with a suspension of a hydrogel and then blended with 20% sandy clay loam soil. It was compacted to 95% Proctor in 15 cm lifts (Bassuk et al. 2015).

The level of soil compaction was verified by an independent construction consulting firm (ESP Associates P.A. Fort Mill SC). Due to the level of soil compaction and the available space in each plot, the amount of non-compacted soil that was installed varied by treatment (Table 1).

Treatment	Volume of non-compacted soil installed (m^3)
Control -Non compacted	2.1 b
Strata cell	1.8 a
Silva cell	2.0 b
Sand BSS	2.5 c
Gravel BSS	2.5 c
Control -Compacted	2.5 c

Table 1. The amount of non-compacted soil that was added to each plot. The space available in each plot was 1.1 m^3. Numbers with the same letter indicate that there are no significant differences among treatments (SNK p=.05).

Containerized, 18 mm caliper *Liriodendron chinense* were bare rooted and installed on 19 August, 2014 in the center of each plot. A 5 cm thick layer of fiber reinforced concrete was then poured over the entire plot surface. A 20 cm diameter hole in the concrete was centered on each tree. The open controls had a 1.3 m square opening.

A soil moisture sensor (Spectrum SMEC 300) was installed in one replicate of each treatment. They were connected to a WatchDog 2400 Mini Station data logger (Spectrum Technologies, Aurora, IL). Irrigation water was automatically applied when soil moisture levels dropped below 10% VWC in 2014 and 2015, and 5%VWC in 2016. Water was applied for ten minutes, up to four times per day from two - one gallon per minute emitters (Rainbird SW-10) in all plots except the SBSS plot. In that plot, an equal amount of water was emitted from a loop of perforated tubing (Rainbird ET63-100S). No irrigation was applied to any treatment in 2017.

Tree growth was measured annually at the end of the growing season. Measurements collected were caliper at 15 cm above grade, tree height and crown spread. Foliar color was assessed periodically using a visual inspection and a SPAD 502 chlorophyll meter (Spectrum Technologies, Aurora, IL).

On 23 October 2017, all leaves were removed from the trees, the trees were severed at the root collar, and concrete plot covering was removed. Soil moisture was measured at 15 cm depth intervals using a Fieldscout TDR 350 with 12 cm rods (Spectrum Technologies, Aurora, IL). Root systems were excavated using high pressure air and water on 24-25 October 2017. Horizontal root spread and vertical root depth were measured. The number of roots near the trunk of the tree that were greater than 1.2 cm diameter were counted. The tops and root systems of each tree were weighed.

Results

Study 1

There were no difference in tree size or color at the time of planting. In 2007, there was high mortality in the expanded slate plot, so all trees in that treatment were removed. Beginning in 2011 there were significant growth differences among the treatments that continued until the end of the study. The supported pavement treatment trees were significantly larger in all growth metrics than other treatments (Photograph 1, Figure 3 and 4). The ESSS treatment tended to have the least amount of growth. The color ratings as expressed by SPAD readings varied by year and were not consistently enhanced for any individual treatment (Figure 5). Visual rating of foliage color was significantly higher for the supported pavement treatment from 2004 through 2012 (Figure 6). The GBSS treatment was no different from the supported pavement treatment in 2004 and 2005.

Photograph 1. Study 1 five years after planting in 2009. Treatments are supported pavement, expanded slate structural soil (ESSS), compacted control (CC), gravel based structural soil and (GBSS). The unlabeled plot was a replacement for the expanded slate plot where the trees died. The smaller plants are magnolias that replaced the original cherry trees in 2007.

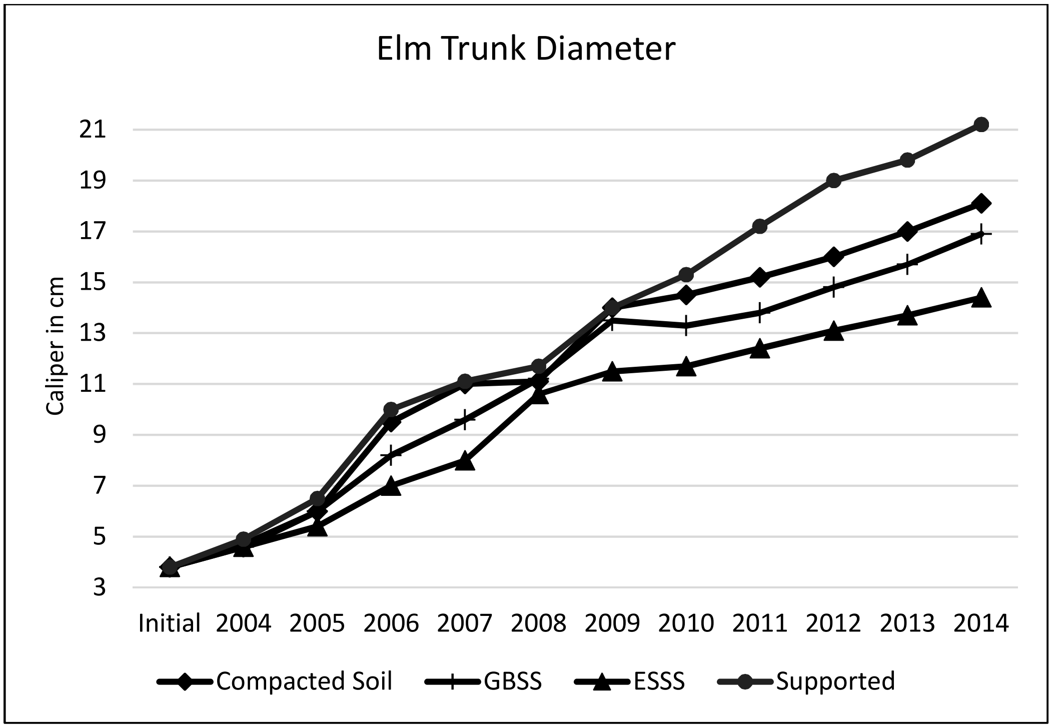

Figure 3. Mean elm trunk diameter (caliper) measured at 15 cm above grade at the end of the growing season. The supported pavement treatment had significantly larger caliper than all other treatments from 2010 through 2014 (SNK p=.05).

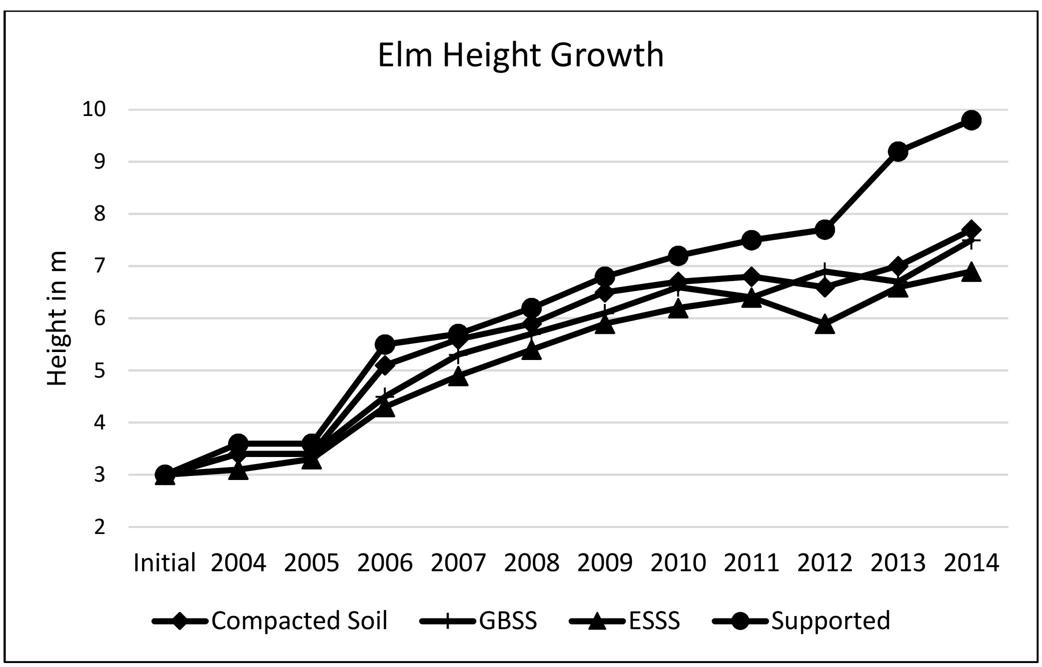

Figure 4. Mean elm height measured at the end of the growing season. There was significantly more height growth with the supported pavement treatment from 2010 until the end of the study(SNK p=.05).

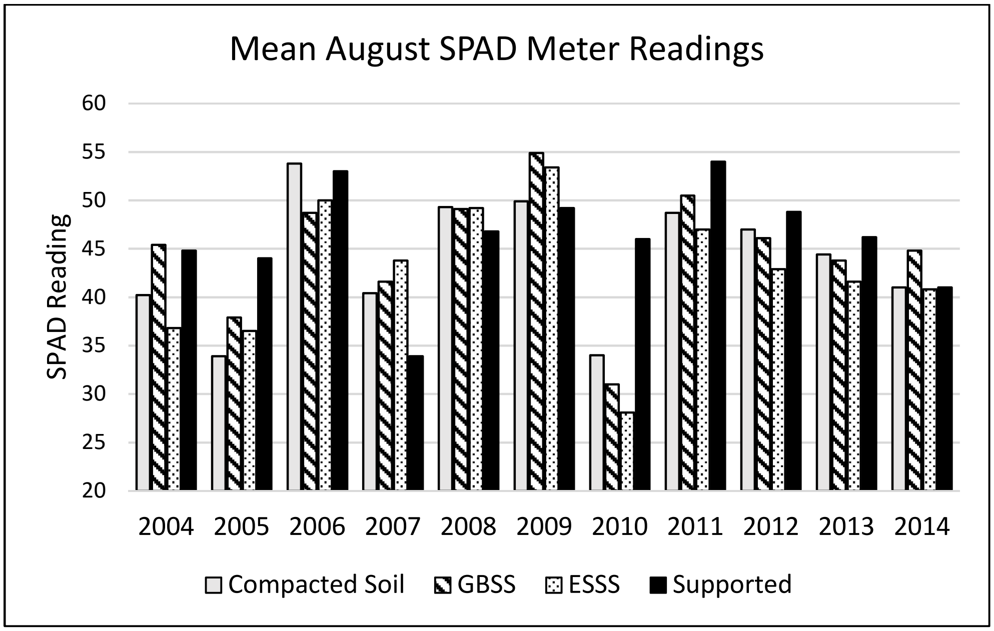

Figure 5. Mean elm foliar color readings as measured with a SPAD 502 chlorophyll meter (Spectrum Technologies, Aurora, IL)

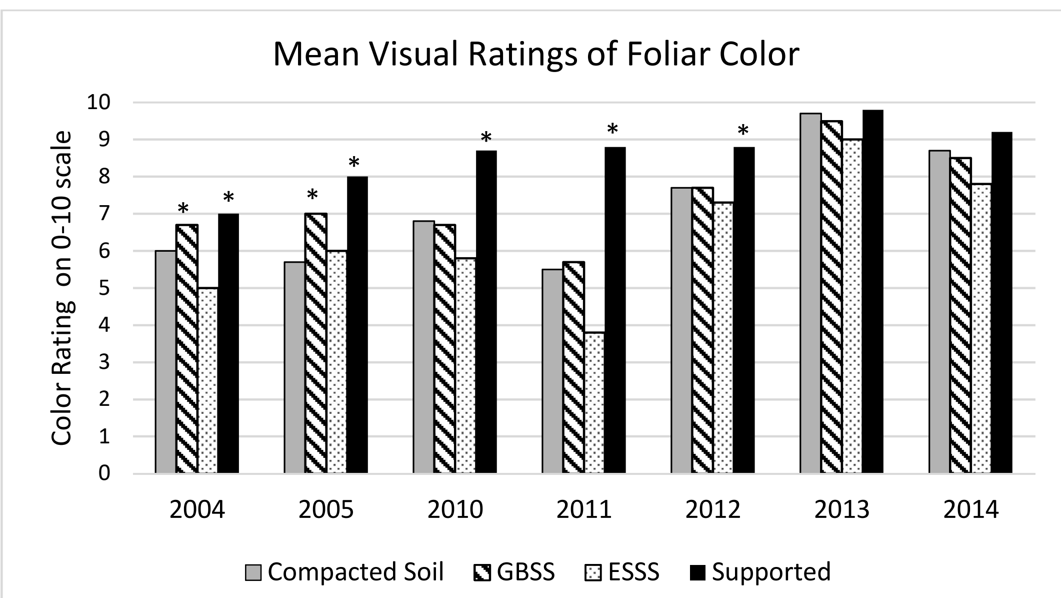

Figure 6. Mean visual foliar color rating based on a 0 – 10 scale with 0= dead and 10= dark green. Asterisk indicates mean is significantly different than other treatment (SNK p=.05).

The number of cracks counted in the concrete surrounding the tree were significantly higher in the GBSS treatment than the other treatments (Table 2).

Treatment	Number of replicates	Mean Number of Cracks in the Concrete per replicate
Compacted soil	6	0.17 a
Expanded slate structural soil	6	0.83 a
Supported concrete	6	1.00 a
Gravel based structural soil	6	2.83 b

Table 2. Concrete cracking associated with soil treatments and tree root growth. Numbers with the same letter indicate that there are no significant differences among treatments (SNK p=.05).

Study 2

Tree growth and health

There were no differences in tree size or color at the time of planting in 2014. At the end of the 2015, the Stratacell, Silva Cell and open control tree size started to diverge from the other treatments (Photograph 2, Figure 7 and 8). In 2016 and 2017, Silva Cell, Stratacell and the open control caliper (Figure 7), height (Figure 8), and spread (data not presented) were significantly larger than the other treatments.

With color ratings, the mean SPAD readings tended to be higher with the Silva Cell, Stratacell and open control (Figure 9). In 2015 the Silva Cell and Stratacell readings were significantly higher than the other treatments. In 2016 the compacted control and GBSS treatment were significantly lower. In 2017 the GBSS reading was significantly lower.

With the mean visual color ratings, the SBSS was consistently the lowest of the treatments, and the Stratacell, Silva Cell and open control were the highest (Figure 10).

Photograph 2. Study 2 two years after planting in 2016. One of the six replicates is labeled by treatment.

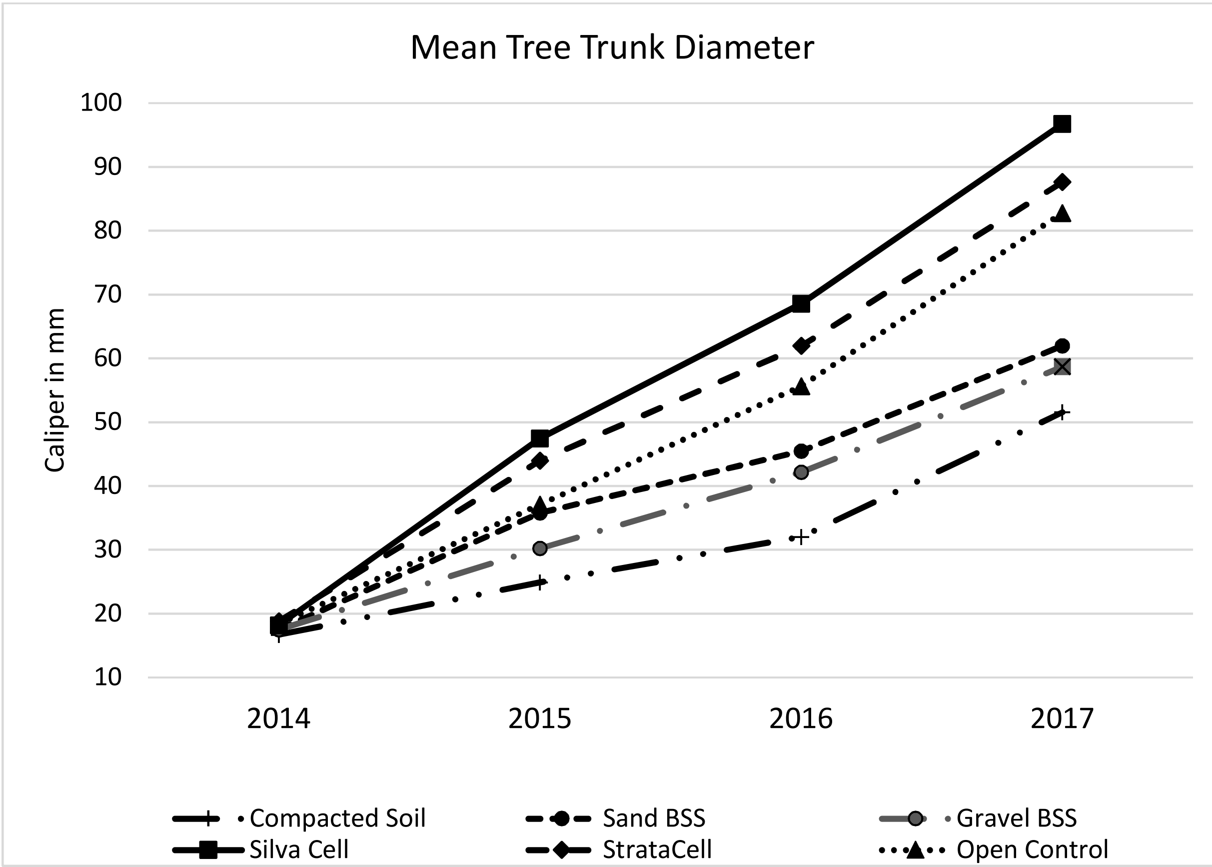

Figure 7. Mean *Liriodendron* trunk diameter (caliper) measured at 15 cm above grade at the end of the growing season.

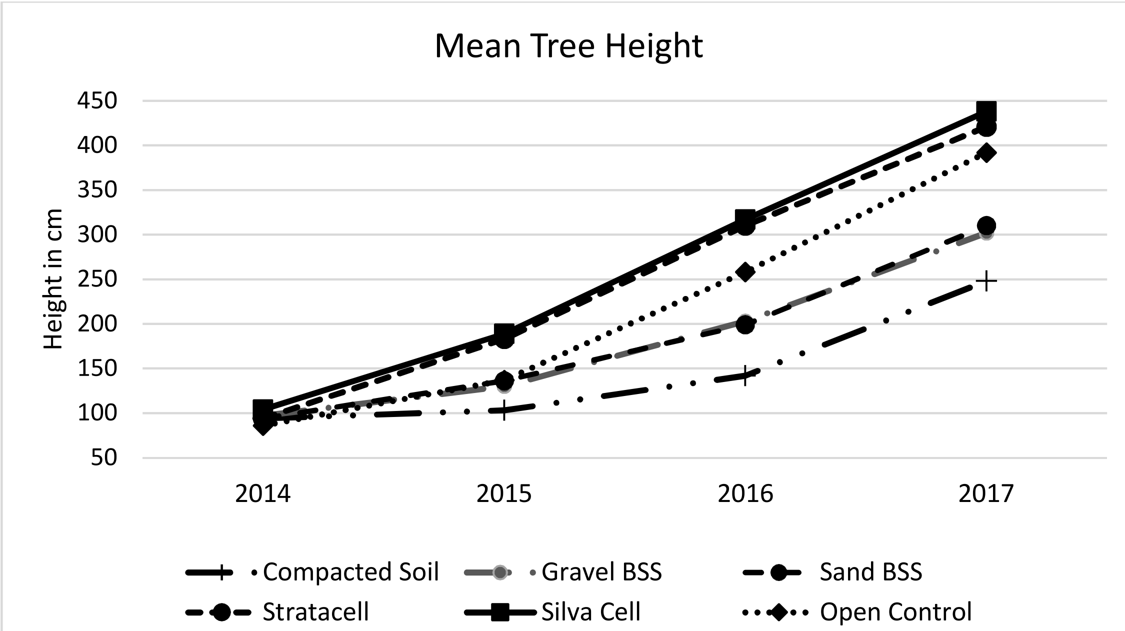

Figure 8. Mean *Liriodendron* height measured at the end of the growing season.

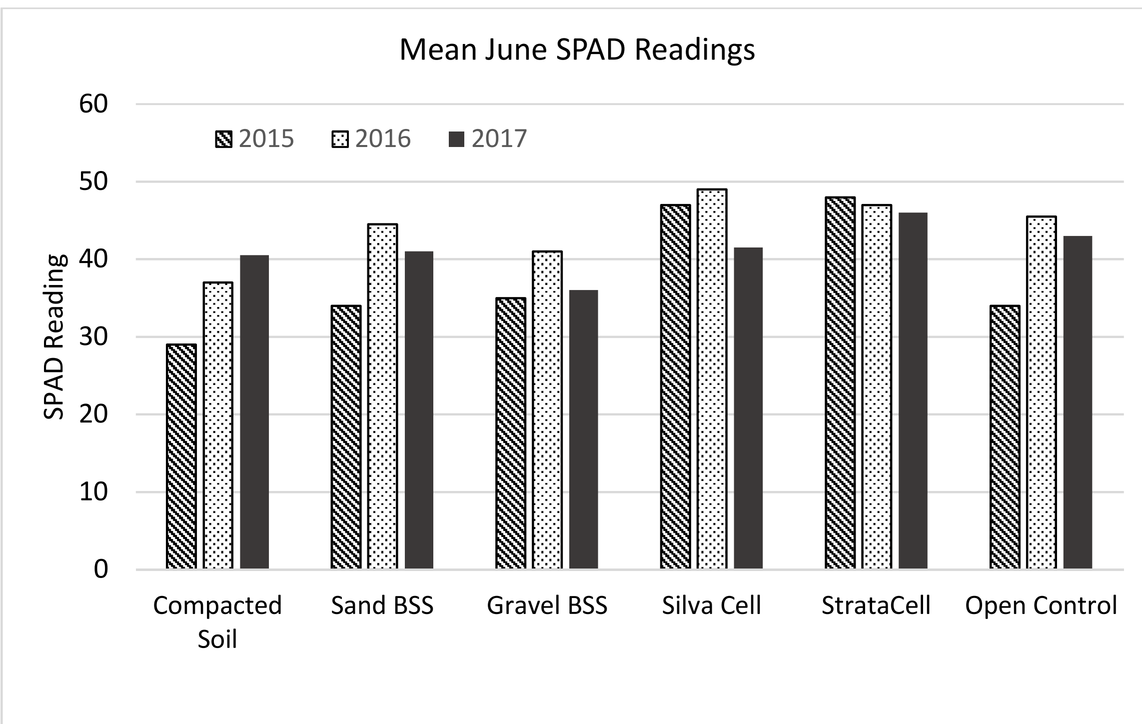

Figure 9. Mean mid-June *Liriodendron* foliar SPAD readings. In 2015 the Silva Cell and Stratacell treatment readings were significantly higher than the other treatments. In 2016 the compacted control and GBSS treatment readings were significantly lower than the remaining treatments (SNK p=.05). In 2017 the differences were not significant.

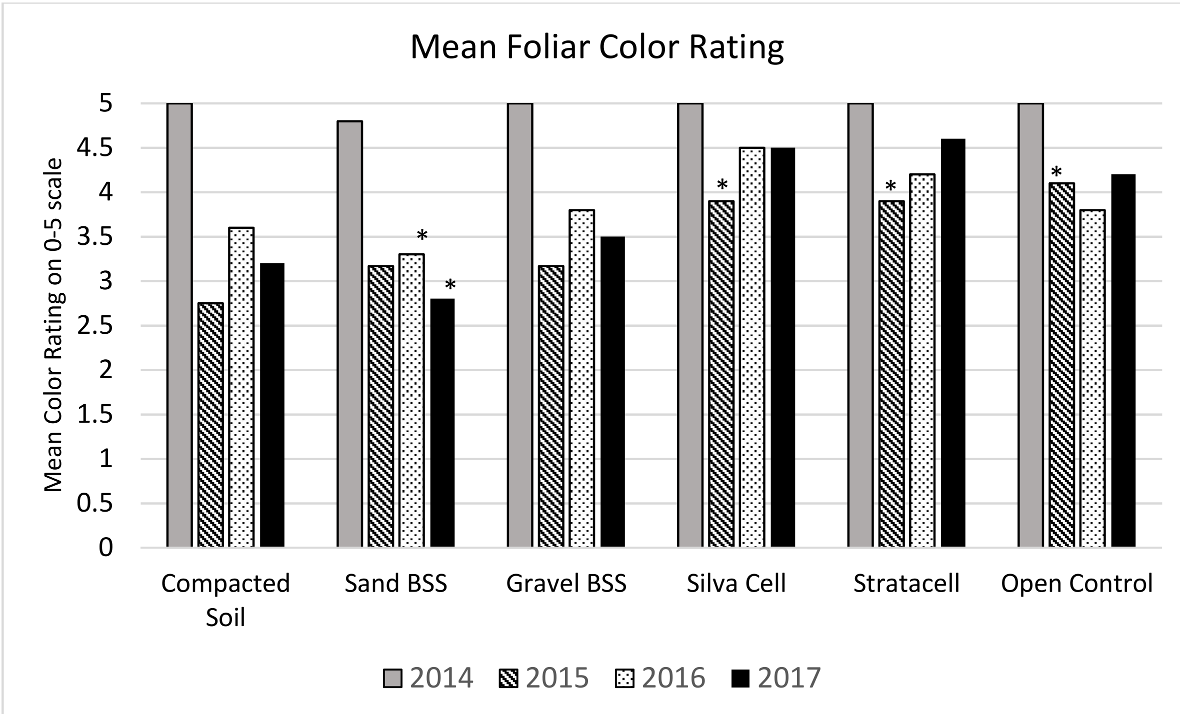

Figure 10. Mean September foliar color visual rating based on a 0-5 scale (0=dead, 10= dark green). Bars with an asterisk above are significantly different from other means in that year (SNK p=.05).

Root growth

The number of roots over 1.2 cm diameter near the trunk was significantly larger in the Silva Cell treatment and there were significantly fewer large roots in the compacted control, GBSS, and SBSS treatments (Figure 11).

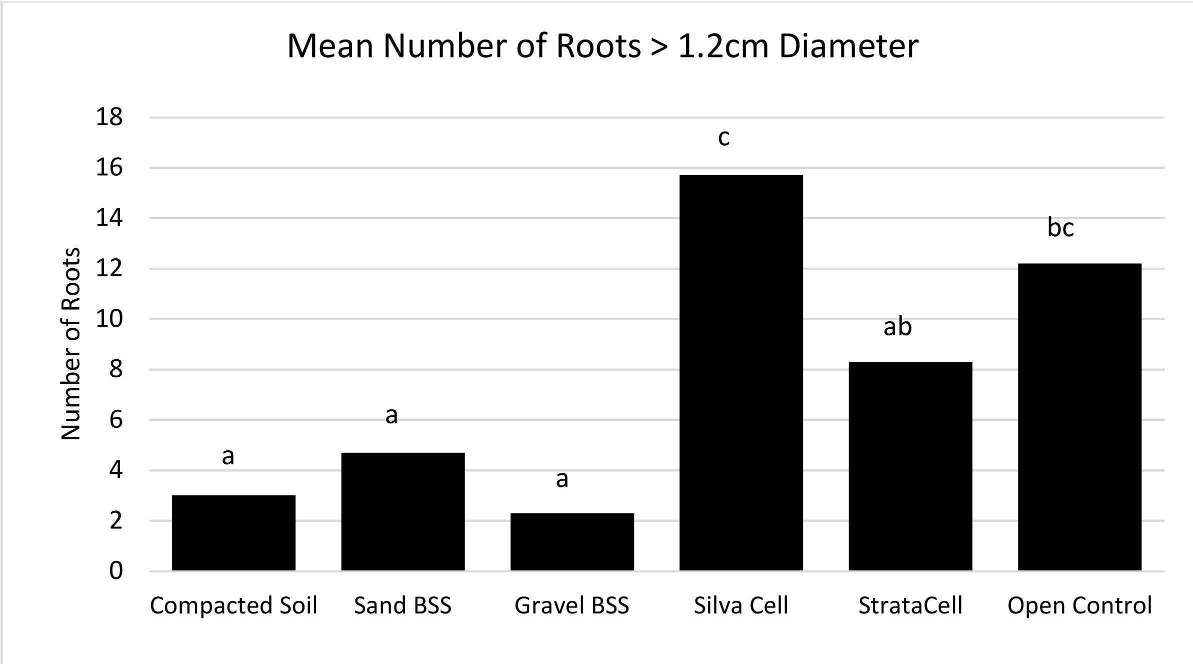

Figure 11. The mean number of roots close to the base of the *Liriodendron* that were greater than 1.2 cm in diameter. Letter indicates that there are no significant differences among treatments (SNK p=.05).

There was no significant difference in root spread when measured across the pavement, but root growth parallel to the pavement was significantly longer with the Silva Cell treatment. There was less root growth in that direction with the compacted control, SBSS and GBSS treatments (Figure 12).

Roots grew significantly more deeply into the soil with both the Stratacell and Silva Cells (Figure 13). The compacted control has significantly less root penetration.

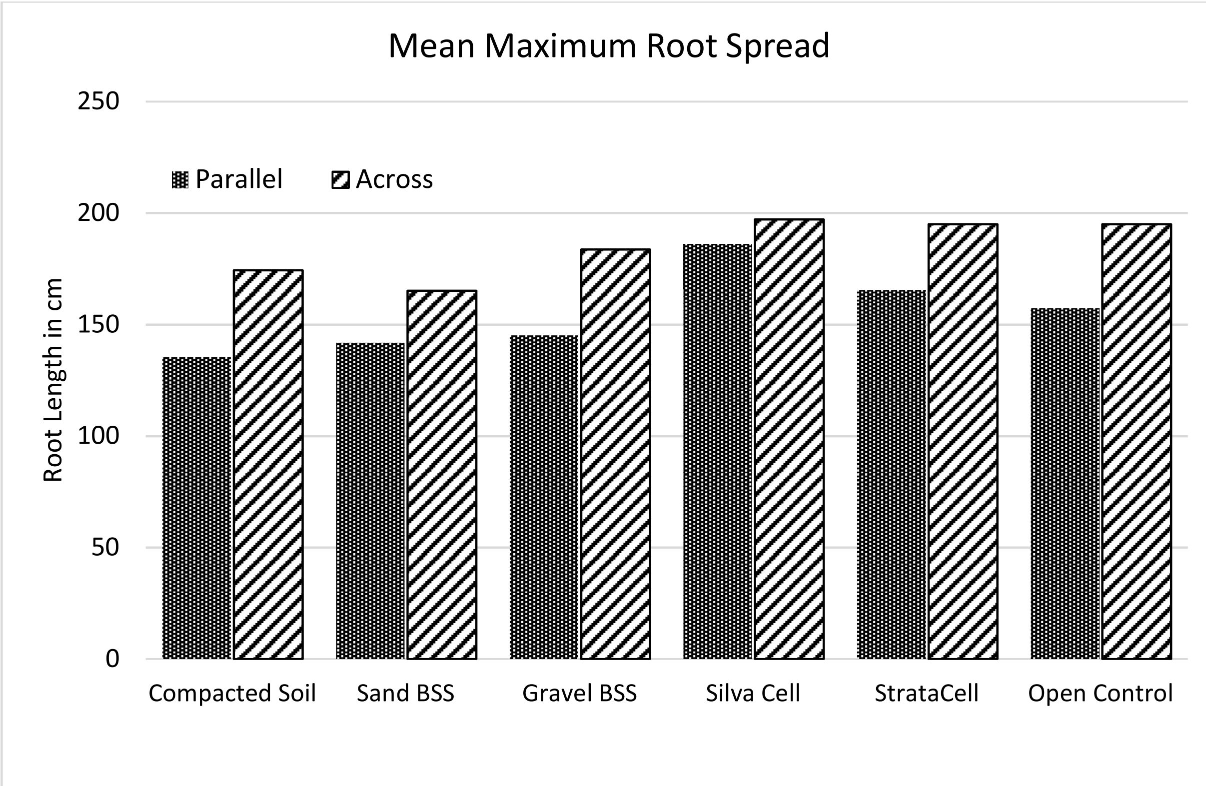

Figure 12. Mean maximum length of root growth measured parallel to the direction of the concrete or across (perpendicular) to the concrete.

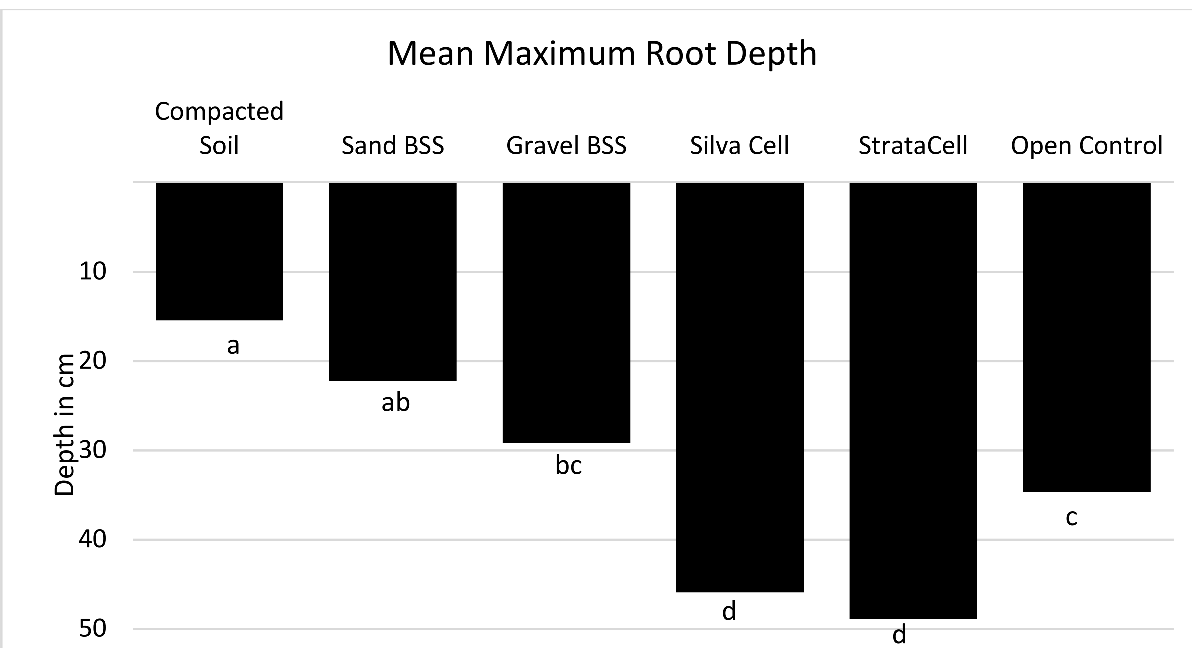

Figure 13. Mean maximum depth of root growth. Letter indicates that there are no significant differences among treatments (SNK p=.05).

Tree part weights

There were significant differences in the weight of the above and below ground parts of the tree based on treatment (Figure 14). Weights separated into two groups with the Silva Cell, Stratcell and open control being significantly heavier and the compacted soil, SBSS and GBSS being lighter.

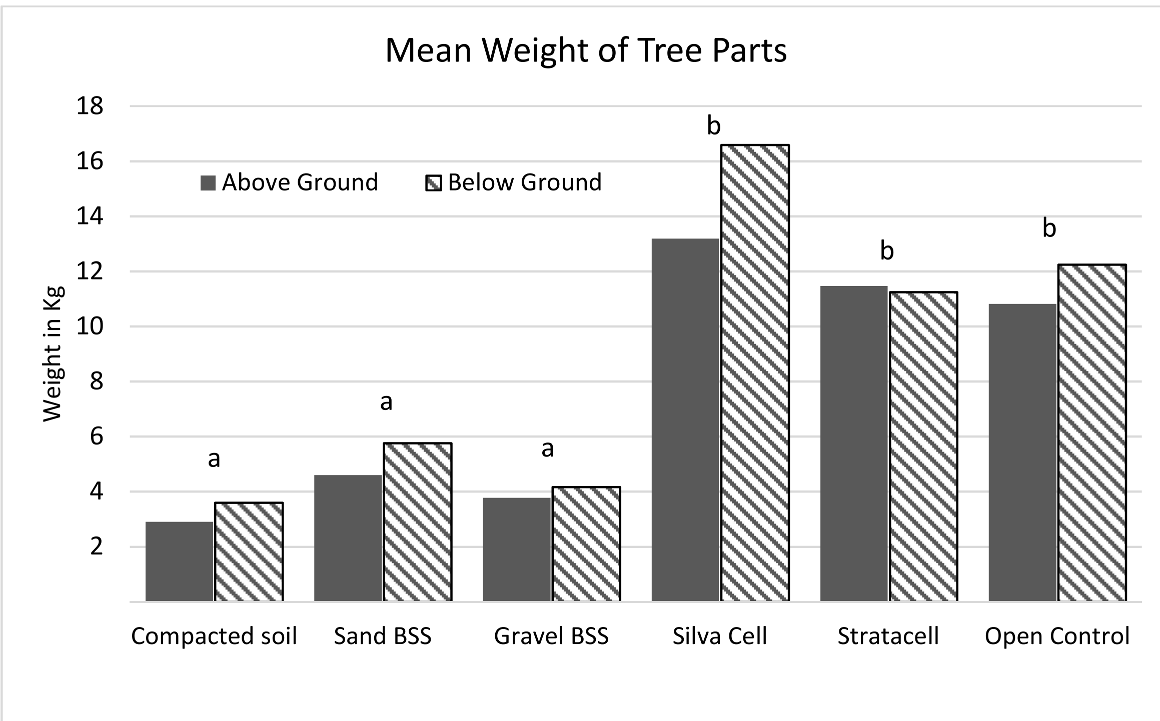

Figure 14. Mean weight of the above and below ground portions of the tree. Numbers with the same letter indicate that there are no significant differences in the weight among treatments (SNK p=.05).

Soil conditions

The compacted control treatment had a higher volumetric water content than the other treatments and the SBSS treatment was the driest (Figure 15). Generally, there was more water at the soil surface than in the lowest level measured. Water content could not be measured in the GBSS treatment using this TDR tool.

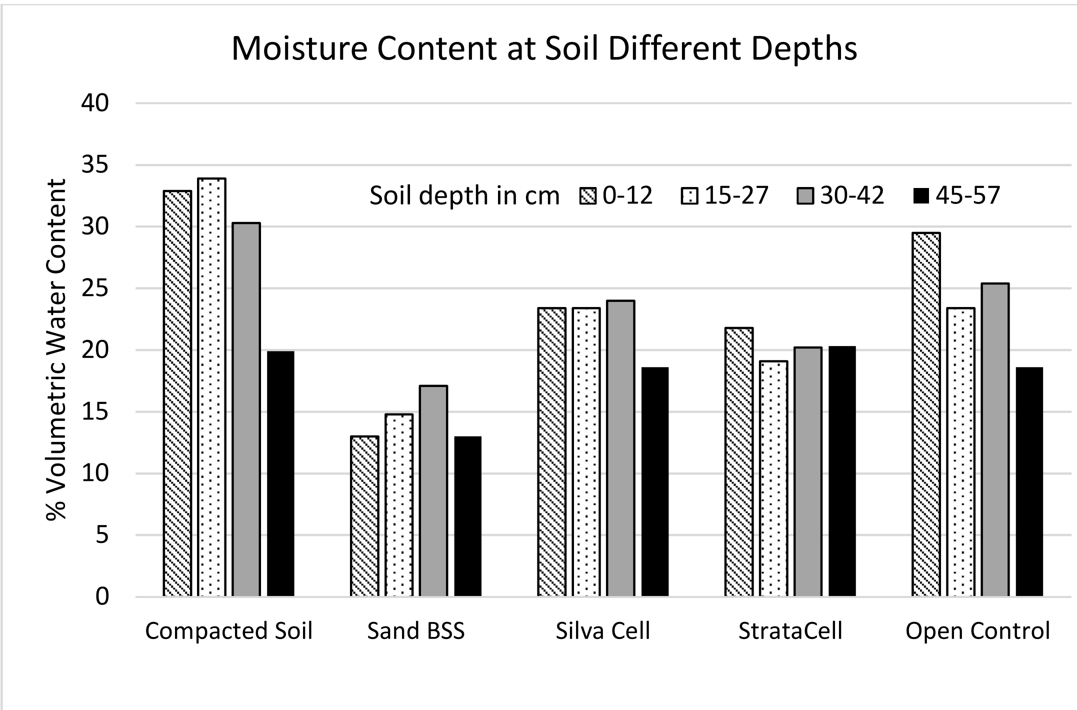

Figure 15. Mean soil volumetric moisture content as measured with a Fieldscout TDR 350 with 12 cm rods (Spectrum Technologies, Aurora, IL).

There was a noticeable amount of soil subsidence beneath the bottom of the pavement in some treatments (Table 2). The highly compacted treatments (compacted control, SBSS and GBSS had less subsidence than the treatments that were not compacted to 95% Proctor.

Treatment	Subsidence Gap below the Concrete Pavement in cm
Comp. Control	0.0 a
Sand BSS	0.1 a
Gravel BSS	0.4 a
Stratacell	1.5 c
Silva Cell	0.6 b
Open Control	0.9 b

Table 2. Mean soil subsidence, measured from the bottom of the concrete to the top of the soil in cm. Numbers followed by the same letter are not significantly different SNK p= 0.05.

Conclusions

In general, the greatest amount of tree growth and healthier trees were seen in non-compacted, low density soil media treatments, either under supported pavement or with an open soil surface. There were no growth or health differences based on the system that supported the pavement.

Lesser growth was seen in trees growing in compacted soil media. When the soil media was compacted, regardless of the substrate, there was less growth and a generally a less healthy appearance aboveground. This is consistent with other studies that have shown the negative impacts of soil compaction (Kristoffersen, 1999, Smiley et.al. 2006, Rahman, 2013, Fite et.al. 2014, Urban and Smiley, 2016).

In Study 1, the supported pavement treatment trees grew trees larger and generally appeared healthier than the other treatments. Trees planted in the compacted soil treatment did surprisingly well considering the soil density. When the cherry trees were removed from this treatment, it was seen that the roots did not penetrate the compacted soil but rather grew upward and outward from the edge of the root ball, likely finding lower density soil at the edge of the plots.

Trees in the ESSS plot grew less well than trees in the GBSS plot. This may be due to the smaller size of the stone, which could result in less space between stones and a higher level of soil compaction (Grabosky and Bassuk, 1995 and 1996).

Trees planted in the 100% expanded slate media had a high mortality rate, resulting in the plot being removed from the study in 2007. This mortality was most likely based on the amount of water retained by the porous stone. That treatment would not be considered acceptable in most urban situations unless water was carefully managed.

Concrete cracking was significantly greater in the GBSS treatment. Smiley (2008) showed that a GBSS treatment is more likely to result in concrete sidewalk cracks based on the trees production of fewer, but larger diameter roots.

In Study 2, the tree growth differences based on soil media treatments were more obvious than in Study 1. This may be attributed to this tree species selection. *Liriodendron* are fast growing in the Charlotte, NC region, are known to have a root system that does best in low density, sandy soils and that are inhibited by higher densities (Francis, 1979).

Treatment based growth differences in general separated into two groups. The open control, Stratacell and Silva Cell treatment trees grew significantly larger than the compacted soil, GBSS and SBSS treatments. When there were differences in foliar color, it followed the same pattern with the open control, Stratacell and Silva Cells being a healthier green color.

Root growth differences were seen in the mean maximum root depth, counts of roots greater than 1.2 cm diameter, and with overall weight of the root system. With the count of larger roots, the greatest number were found in the Silva Cell treatment, followed by the open control and Stratacell. With root depth, the Silva Cell and Stratacell treatments had significantly more roots deeper in the soil. Overall root weight was significantly greater with the Silva Cell, Stratacell and open control treatments.

Root differences are likely based on soil density and oxygen availability in the soil profile. Soil moisture does not appear to be a factor since the highest and lowest soil moisture level were found in the compacted soil and SBSS treatments, respectively, both of which had lower levels of root development. The Silva Cell and Stratacell treatments had moderate moisture contents and the open control had higher moisture level near the surface. This high moisture at the surface can be attributed to the non-coved surface that the other treatments did not have.

The soil beneath the pavement subsided more when the soil was not heavily compacted. The compacted control, SBSS and GBSS treatments has significantly less subsidence than the other treatments. The Stratacell treatment experienced much more subsidence than all other treatments. This was attributed to the redistribution of soil with the infiltration of rain water. It was noticed that with the first three large rain events after tree planting, the trees in this treatment were moved deeper into the soil as the soil beneath them washed into other portions of the Stratacell structure. Those affected trees were replanted at the original depth after the addition of more soil. In one replicate a shed snake skin was found partially under the pavement, which points to potential problems with having a large gap.

Summary

Soil treatments that provided a low density growing media resulted in the largest and healthiest trees. There are multiple ways to achieve the goal of low density soil beneath pavement including: not paving over the soil surface, and providing a bridge over the surface with low density soil beneath. Our research did not point to a “best product” to achieve this goal. Rather, this study reinforces the idea that any of the methods that provide support for the intended load on the pavement and keep the load off the growing media worked well. When designing and installing a supported pavement system, it should be kept in mind that low density soils will self-compact to some degree resulting a subsidence and the formation of a gap between the soil surface and the bottom of the pavement. That gap can provide habitat for unwelcome urban wildlife.

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