deeproot

Growth Rates and Performance of Trees in Silva Cells

Case study of nearly 400 trees at 10 locations, after 2 to 6 years

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Introduction

Green utilities like soil, trees, and water can provide a high level of ecosystem services while creating a more livable urban environment for people, but designing spaces that satisfy the needs of both natural and built systems can be a challenge. The abundance of paved surfaces often leaves urban trees with limited access to poor-quality soil that limits growth. According to a 2007 study by Dr. Kim Coder, "Soil compaction is the most prevalent of all soil constraints on shade and street tree growth…Many people become obsessed by small constraints on trees while major life-altering impacts are ignored. Soil compaction is one of those major problems causing significant tree stress and strain, and whose impacts are usually blamed on other things." According to the same study, the top three factors that cause growth limitations for trees, by a wide margin, are soil water availability, soil aeration, and soil drainage — all three of which are linked to soil compaction.

DeepRoot developed the Silva Cell, a modular suspended pavement system for containing unlimited amounts of healthy soil beneath paving while supporting traffic loads and accommodating surrounding utilities, to help solve this challenge. By combining on-site stormwater management with expanded rooting volumes, Silva Cells provide an opportunity to grow large, healthy trees and restore ecological function, even in dense urban environments.

In order to document the growth and performance of trees in Silva Cells, and to validate our own approach to designing for both trees alone and trees-and-stormwater in combination, we undertook a research and monitoring study of 10 Silva Cell projects across North America. At the time of data collection it had been eight years since the first commercial Silva Cell installation – long enough to have built a great variety of projects – allowing us to assess tree performance and to compile lessons and best practices to guide future efforts. In this time, approximately 1,000 installations have been constructed. We estimate that those projects include more than 18,000 trees.

Silva Cells advanced the available methods for providing rooting space under pavements by making larger volumes of good horticultural soil available to the tree. The space efficiency of the structure means that less space is required in order to provide target soil volumes, and the design accepts a wide range of soil types that are at optimum compaction for root growth. But how well do the trees grow when compared to open-grown trees (trees growing on wide spacing with little canopy competition) in similar soil? This study examined nearly 400 trees that had been in the ground between two and six years to see how well they have grown relative to open-grown trees of similar species in good soil environments not surrounded by pavement.

Previous attempts to improve rooting of trees under pavements have taken two directions.

One approach is suspended pavements, where the soil is not fully compacted and the pavement is suspended over the soil either by designing the pavement to bridge over the loose soil, or supporting the pavement with a structure such as piers, posts, or other structural shapes. Silva Cells are a variation of this direction. The second approach, structural soil, provides the structure within the soil itself (in structural soil's case, this is done using rock) in order to support the pavement while still allowing the needed root space.

Suspended pavements that use the pavement bridging approach are limited by the practical width of the bridge structure. As the bridge becomes wider, it costs more to build. Custom designed and built structures often require significant engineering design to meet city standards. In addition, stronger structures become increasingly expensive to maintain should utility work be needed under or near the structure. Silva Cells solve these problems by using a pre-engineered structure that is easy to fit below paving, where competition for space is intense. Its modular, independent structure fits around, between, and even within other infrastructure including streetlight footings, utility lines, and manholes. The system can easily be adopted into city standards, such as the 2012 City of Toronto recommendations for tree planting in hard boulevards.

The structural soil approach has two variations. The first uses large, crushed rock that is selected to fall within a narrow size range as the structure, with the rooting space filling the void spaces between the stones. The second uses narrowly graded sands that allow the roots to penetrate small spaces in the sand and then expand. Each of these structural soil approaches has evolved with a fairly wide variation in specifications and formulations.

All of these ideas have been in use for sufficient time to test how well they are performing in urban conditions. Smiley (personal communication) found that trees in large suspended pavements grew equally well as trees in suburban tree lawns. Smiley/Urban found that trees in sand structural soil generally grew slower than trees in both suspended pavements and open planters (Smiley/Urban 2014). The City of Stockholm found that trees in rock-based structural soil grew well but require very large volumes of material (Stockholm 2009) and Fite et al, found that trees in suspended pavements grew better than sand structural soils and rock structural soils (Fite et al 2014).

There has also been some controlled research on comparing the different approaches.

Bassuk et al found that roots grow into the void spaces of the rock (Bassuk 1995), and later (Bassuk 2003) found that tree growth was limited to the volume of the soil between the rock, which caused the rock-based structural soil to require significantly more material than loam soil to achieve similar results. Smiley, in an ongoing research project, found trees in Silva Cells grew significantly better than trees in sand structural soil and rock structural soil (Smiley 2016) and that trees in Silva Cells grew somewhat better than trees in Strata Cells, which is a segmented, small compartment, structural system. Smiley in an earlier study found that trees in suspended pavement grew better than trees in rock structural soil (Smiley 2006). Rahman found that trees planted in loam soil in open planters grew better than trees in sand soils under pavement, and much better than trees in suspended pavement where the structure was highly segmented into small compartments (Rahman 2013).

In order to connect these previous studies to the Silva Cell concept, the following study was undertaken. The study examined 18 different tree species growing in Silva Cells in urban streetscapes and public spaces in a variety of regions and climates across the United States and Canada. The intent of the study will be to document the performance of the trees over a multi-year period.

MEANS AND MATERIALS

STUDY DESIGN

We sought to undertake a comparative study that records and evaluates the performance of a large number of trees planted in Silva Cells in built landscapes across many climates and urban situations. The group of 10 study projects were selected based on the following criteria:

- Sufficient data on construction to reasonably understand what was built;
- Trees well established in the first several years (to control for establishment care);
- Geographic accessibility;
- Diverse locations and climates;
- Diverse site types;
- Diverse species;
- Diverse irrigation methods;
- Minimum average of 350 cubic feet (9.9 cubic meters) of soil per tree.

The intent was to make the study large enough to account for variations in urban environments, maintenance, and surrounding soil conditions. The projects were all located in the USA and Canada, encompassing varied climates including Mediterranean, arid/desert, cool temperate, and warm temperate. The total number of trees in the study was 408. 16 of these trees were excluded from the analysis because they were dead or nearly dead. Thus, all statistics in this paper — with the exception of the "Tree Condition (Overall)" chart, are based on a sample size of 392 trees. The number of trees on each project ranged from as few as 7 to as many as 180. Projects had different methods of watering, including bubblers, pervious pavers, drip irrigation, irrigation at tree opening, and irrigation under paving. Two projects (South East False Creek and Ft. Saskatchewan) contained over half of all the trees, but these projects had many sub areas that allowed examination of different species and planting conditions.

The following is a list of the surveyed projects.

NAME	LOCATION	INSTALLATION DATE	DESIGN FIRM	# OF TREES	# OF DEAD/ DYING TREES	# OF TREES INCLUDED IN GROWTH RATE ANALYSIS
South East False Creek Olympic Village	Vancouver, BC	Fall 2009	PWL Partnership	180	4	176
Ft. Saskatchewan Phases 1 & 2	Ft. Saskatchewan, AB	Fall 2010 (Part 1)	DIALOG	66	5	61
Marquette and 2nd	Minneapolis, MN	Fall 2009	SEH, Inc.	36	3	33
Sugar Beach	Toronto, ON	Spring 2010	Claude Cormier + Associates	33	4	29
North Tucker Boulevard	St. Louis, MO	Fall 2011	HDR	28	0	28
Sundance Plaza	Fort Worth, TX	Fall 2013	Michael Vergason Landscape Architecture	18	0	18
Martin Luther King, Jr. Memorial	Washington DC	Fall 2011	Oehme van Sweden	16	0	16
Haas Business School	Berkeley, CA	Spring 2013	GLS Landscape Architecture	12	0	12
UNC Bell Tower	Chapel Hill, NC	September 2011	Cole Jenest & Stone	12	0	12
Neyland Stadium	Knoxville, TN	August 2010	Carol R. Johnson Associates	7	0	7
TOTAL				408	16	392

DATA COLLECTION

Trees were visually inspected, measured (diameter at breast height, or DBH), and photographed. Each tree was assigned a numerical health rating. Data was recorded by regional collaborators who visited the site to collect the data. Collaborators are noted at the end of this paper.

All site data was collected between May and September of 2015.

COLLABORATOR CONSISTENCY

All collaborators were trained in basic tree assessment and data collection, whether through classroom time studying arboriculture or landscape architecture, or through field experience. A complete list of the names of the collaborators, and their qualifications, can be found at the end of this paper.

Collaborators were supplied with written instructions to make consistent observations. Detailed PowerPoint presentations of each of the ten projects were developed to define the area of study and the conditions at the site. They included a plan view of the site, the location of each Silva Cell tree based on Google street view information, a numbering system for each tree, photos from previous visits (if any), and any other notable site features or conditions.

TRUNK DIAMETER

The DBH measurement point (4.5 feet, or 1.37 m, above the ground) is a standard measuring point in arboriculture as it reduces the degree of inaccuracy caused by measuring closer to the ground, where the trunk is tapering more rapidly. At 4.5 feet (1.37 m) above the ground, slight differences in the height of the measurement do not produce significant differences in the data. At many sites the tree rootball was below pavement or under tree grates, making accurate determination of the soil level at the top of the rootball difficult. Anticipating the rootball below paving issue, and that many trees have buried trunk flare and other complications from nursery production, installation, and maintenance, collaborators recorded any problems encountered when trying to determine the height above the soil line. Rather than trying to estimate depth of the rootball below the paving, all trees where the paving covered the rootball were measured 4.5 feet (1.37 m) above the paving elevation.

A diameter tape was used to collect the DBH measurements. Diameter readings were recorded on a standard excel sheet pre-populated with the tree numbers for the collaborator.

ESTIMATE OF TREE TRUNK DIAMETER AT TIME OF PLANTING

In order to calculate the tree growth over time it was necessary to estimate the trunk diameter at the time of planting. The trunk caliper was determined from the contract documents and, when possible, confirmed with the design firm that the trees at installation were reasonably close to the contract requirements. Most of the projects were associated with large construction efforts, and reliable records were available. The projects were also not so old that the design firms were not available, and in most cases some of the original design team members were still there.

The problem of original size is complicated by the fact that the landscape industry uses trunk caliper, or the diameter of the trunk close to the ground (6 to 12 inches, or 15.24 to 30.48 cm depending on the tree size), while the field measurements are made using DBH — the diameter at 4.5 feet (1.37 m) above the ground. Past work by James Urban to develop a method to convert caliper to DBH found that DBH in nursery trees averages about 80% of trunk caliper. This factor was used to convert the provided contract tree size to its probable DBH at the time of planting. The size at planting is further complicated by the fact that caliper size in most planting varies by about 0.5 inches (1.27 cm) across any set of purchased trees.

Each of these factors introduces a slight variable in the reliability of the data. However, each factor — reliability of the institutional memory of the tree size at planting, variation in caliper, and variation in the conversion of caliper to DBH — is just as likely to be slightly larger or smaller than the actual size and is likely to average to an estimated size that is reasonably close to that actual condition. The larger the sample size, the greater the likelihood of accuracy as the plus and minus factors balance. Finally, with each added year of the study period the size of any error in the initial size calculation becomes an increasingly smaller factor in the result.

PHOTOGRAPHY

Each site was photographed in a consistent manner. A photo guide with detailed instructions on optimal ways to take photos in order to capture the tree – for example, avoiding background conflicts that make it hard to see the canopy, or high contrast compositions – was provided. Collaborators were instructed to take at least four photos on each project – one tree in excellent condition, one tree in poor condition, and two trees in average condition – to represent the range of performance, and to provide benchmarking during the analysis phase. Collectors were instructed to label photos with the tree number so that we could refer to the exact location of the photographed tree.

Photos were also used to assess overall site conditions such as a clogged drain, access issues, or nearby construction that could provide clues to better understand tree performance.

TREE SPECIES

Tree species were determined using project drawings, planting plans, and, in some cases, on-site identification. The presence of replacement trees or outdated project documents may mean that different trees were planted than what was identified. To the best of our knowledge, the study sites included the following tree species at the time of data recording.

Acer cappadocicum
Acer freemani
Acer platanoides
Acer rubrum
*Stewartia spp. / Carpinus caroliniana**
Gymnocladus dioicus
Gliditsia triacanthos
Koeleuteria paniculata
Maackia amurensis
Nyssa sylvatica
Platanus x acerifolia
Prunus x yedoensis
Quercus acutissima
Quercus bicolor
Taodium distichum
Ulmus americana
Ulmus crassifolia
Zelkova serrata

*Note that the Stewartia spp. and Carpinus caroliniana trees were planted as a mixed grouping in the data set at the South East False Creek (Vancouver, BC) project and the data was not recorded separately by species. However, there was no significant difference in average growth rates and they were recorded on the graphing as one tree type.

TREE HEALTH CONDITION

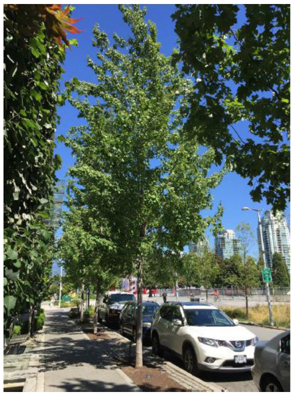
Each tree was visually inspected and rated. A guide was supplied that contained a numbered rating system (1, 2, 3, 4) to designate the tree's condition:

RATING	DESCRIPTION
1	Excellent: Good health, leaves dark green in color and fully covering the canopy.
2	Good: Leaves lighter in color, significant leaf edge browning, not fully covering the canopy, or some twig tip dieback. Damage to trunk or branches from impact.
3	Poor: Leaves much smaller than normal and 25% of branches with dieback or significant evidence of pruned branches in upper canopy (except from removal from the bottom to elevate canopy).
4	Dead, almost dead, or removed: All or more than 50% dead branches, no tree in location, tree significantly smaller than other trees in the stand that would indicated it was planted much later than the others trees/ is a replacement tree.

Assessing tree health in this manner is somewhat subjective and tree health data is primarily for us to better understand the tree condition at the time of the initial observation, and to set a base condition for comparison when the trees are revisited for a follow up study. Health assessments were recorded on a standard excel sheet pre-populated with the tree ID numbers for the collaborator.

EXAMPLES OF TREE HEALTH RATINGS

A tree rated "1" (Excellent) at Haas School of Business in Berkeley, CA.



A tree rated "2" ("Good") at South East False Creek in Vancouver, BC.

A tree rated "3" ("Poor") at North Tucker Boulevard in St. Louis, MO.

A tree rated "4" ("Dead or dying") at Marquette and 2nd in Minneapolis, MN.

Note that the following analysis only included trees that survived. 16 trees (3.9%) out of the 408 trees surveyed deemed to be dead, almost dead, or removed (indicated by a rating of "4") were not included in our statistical analysis. This is a remarkably low percentage of lost trees.

SOIL VOLUME

Soil volume is an approximate average available soil per tree provided by Silva Cells based on the project drawings. Additional available soil not provided by the Silva Cells such as that in the tree opening or in adjacent lawns or medians, and soil with less than optimum rooting potential found under sidewalks, was not counted, making our approximations very conservative.

IRRIGATION

Irrigation type, if present, is based on information in the project drawings.

STORMWATER

Projects that include stormwater treatment within the Silva Cells as taken from the project drawings. This only includes projects where rain water is directed into the soil within the Silva Cells to meet mandated stormwater requirements and does not include projects where rain water is directed into the Silva Cell soil to provide supplemental water for the trees.

ESTABLISHING A TREE REFERENCE GROWTH RATE

In order to evaluate the data, it is important to establish a reference point to gauge average/expected annual tree trunk growth. This study looks at a variety of tree species over a wide range of climates and tree management regimes. However, the intent of Silva Cells is to set a fairly high bar for what are considered successful trees in difficult urban conditions. Making this assessment proved challenging and is, admittedly, subjective. The usefulness of this study will be to serve as a comparison to other trees in the communities where healthy trees are desired. The study hopes to help answer the question: "Are the results achieved by Silva Cells going to make a significant improvement over similar tree performance in the community where the system is proposed?"

There is surprisingly little data in the literature on this topic. Controlled tree studies sometimes include trunk diameter increase data, but these are controlled field conditions that lack the stresses of urban sites. The following are some sources of information on typical annual DBH growth rates.

The nursery industry has good experience on how fast different trees grow in production settings that are optimized for water, soil, and nutrients. Interviews with field-grown tree nursery owners in several areas of the United States reported that growth rates of 0.4 to 0.6 inches (1.01 to 1.52 cm) per year was a reasonable rate of growth for their product. The impact of regular root pruning to stimulate better quality root balls was cited as slowing growth.

Tree reference texts such as Michael Dirr's "Manual of Woody Plants" describe growth by canopy height and width, and often include descriptions of a tree's growth rate as slow, moderate, or fast. Since trunk diameter is related to tree canopy growth, these resources may be useful in comparing species.

Forestry growth rate data considers trees in closely spaced stands with significant canopy and light competition, but typically in good soil conditions. Teck/Hilt found that hardwood species individual annual DBH trunk growth over an average of 11 to 12 years was 0.77 inches (1.95 cm) in the Northeastern United States (Tech 1991).

Tom Perry, one of the first researchers to examine the difference between forest, landscape, and urban trees found that growth rates were highly variable and change with age, slowing as canopy competition increased and/or age extended past about 50 years. Growth rates of 0.5 inches to 0.75 inches (1.27 to 1.90 cm) per year were not uncommon when soil type and volume were adequate and moisture sufficient (Perry 1978).

Smiley/Urban measured the DBH of over 300 street and plaza trees in Boston to examine differences in growth rates. They found that the variety of species of trees in large open planters grew between 0.37 and 0.61 inches (0.93 to 1.54 cm) per year (Smiley/Urban 2014).

The average growth rate determination is further complicated by the fact that newly planted trees almost always grow slightly slower in the first two years while they are becoming established. Layman et al in a study looking at different soil treatments took careful measurements over a large number of trees and different species as part of a soil restoration study (Layman 2016). The study found that the growth rates for the trees in the undisturbed soil in their first two years averaged 0.5 inches (1.27 cm) increase per year for the slowest tree species, and 0.7 inches (1.77 cm) per year for the fastest growing species. Over the next 4 years the average growth rate was 0.7 inches (1.77 cm) increase per year for the slowest species and 1 inch per year (2.54 cm) for the fastest species. The genera used in the study were Acer, Quercus, and Prunus, so the comparison on growth rates in optimum soil conditions would appear to be reasonable.

The more years after planting, the less this effect of the slower establishment period begins to have on the average. The number of growing seasons for the trees in the Silva Cell study varies from two to six years.

Trees growing at sites further south tend to grow more per year than the same species much further north due to the longer growing season. Irrigated trees will grow faster than non-irrigated trees.

Trees growing at wider spacing tend to grow faster than trees closely spaced. Trees in the shade of buildings may grow slower than trees in full sun, however the opposite has also been observed.

Three species -- stewartia, carpinus, and maackia -- are typically slow-growing trees and add trunk diameter at less than 0.5 inches (1.27 cm) per year, even when healthy.

Each of these factors complicates the growth expectation. Based on the above discussion, 0.5 inch (1.27 cm) trunk growth per year will be set as a reasonable, "normal" benchmark to which trees that produce large canopies, such as oaks or maples, growing in Silva Cells can be compared. Trees growing at this rate or faster should be considered as successful trees. This growth rate expectation should also be factored for climate, region, irrigation, and other factors mentioned in the above discussion.

RESULTS

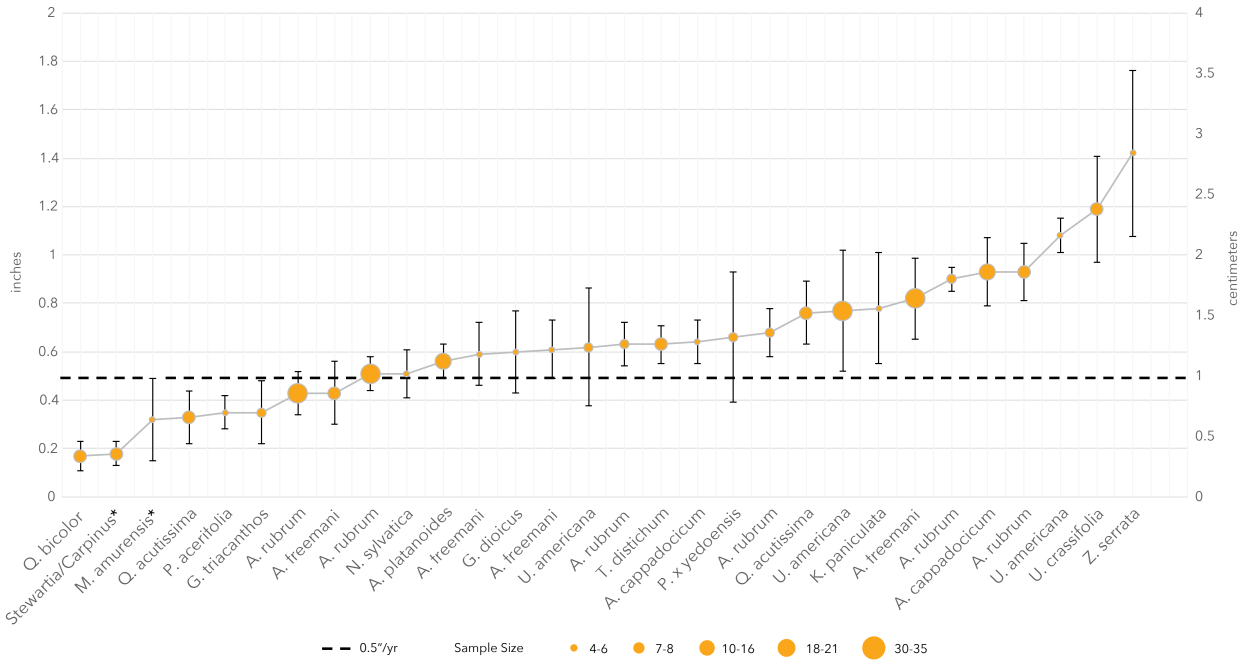
RAW GROWTH RATES

The following are the average growth rates, in inches/centimeters per year, across the different species and projects. This graphing shows overall tree performance. 68% of the trees performed at or above the reference rate of 0.5 inches (1.27 cm) of trunk growth per year, with 29% growing faster than 0.8 inches (2.03 cm) per year, exceeding forest and undisturbed field soils in experimental plots. At the slower growing end of the graph, 28% of the trees grew less than the reference rate of 0.5 inches (1.27 cm) per year, with 11% between 0.4 and 0.49 inches (1.01 and 1.24 cm), 7% between 0.3 and 0.39 inches (0.76 cm to 0.99 cm), and 14% below 0.3 inches (0.76 cm) per year. In the group of trees growing slower than 0.5 inches (1.27 cm) annually, 20 trees (5%) were the slow-growing species of stewartia, carpinus, and maackia.

This graph arrangement of ranking from slowest to fastest will be used to examine other factors to see what may be influencing these results.

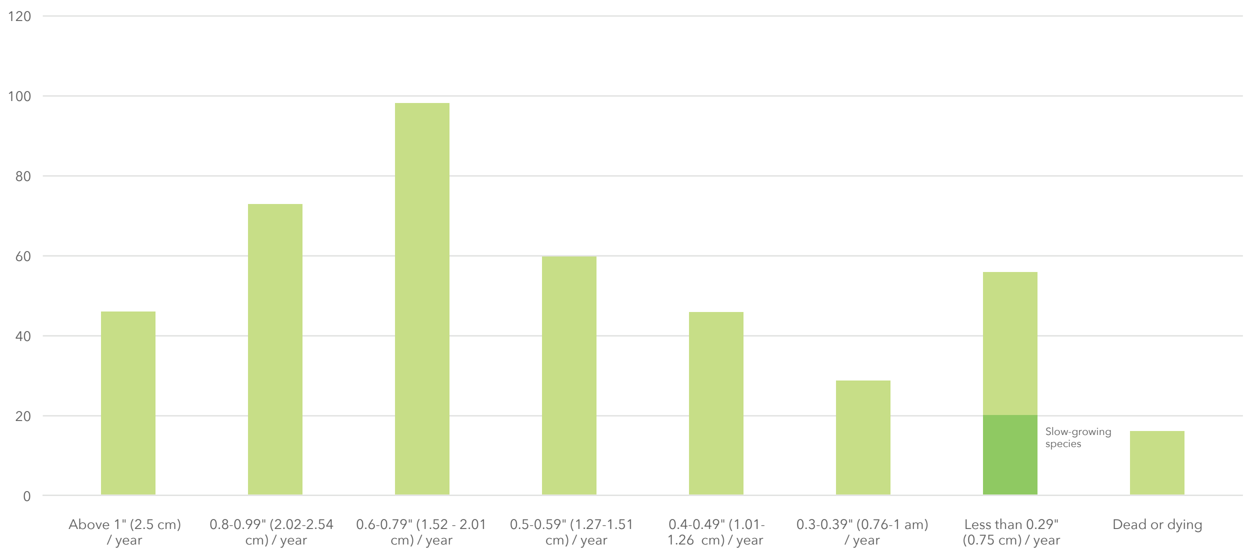
The standard deviation bars are longer than would be expected in a controlled field study. This represents the background clutter from collecting data in real world, publicly constructed, and accessible sites. We accept that this condition exists, making the data less reliable than a controlled study site, but the intent of the study was to test the thesis in real world situations. Trees planted in Silva Cells on average have higher yearly growth rates (mean=.65 inches/year) than the general growth standard, which is 0.5 inches/year (P<0.001) (t-test, Stata version 13.1).

ANNUAL TRUNK DIAMETER INCREASE



* Slow growing species, not considered under-performing

NUMBER OF TREES IN SAMPLE

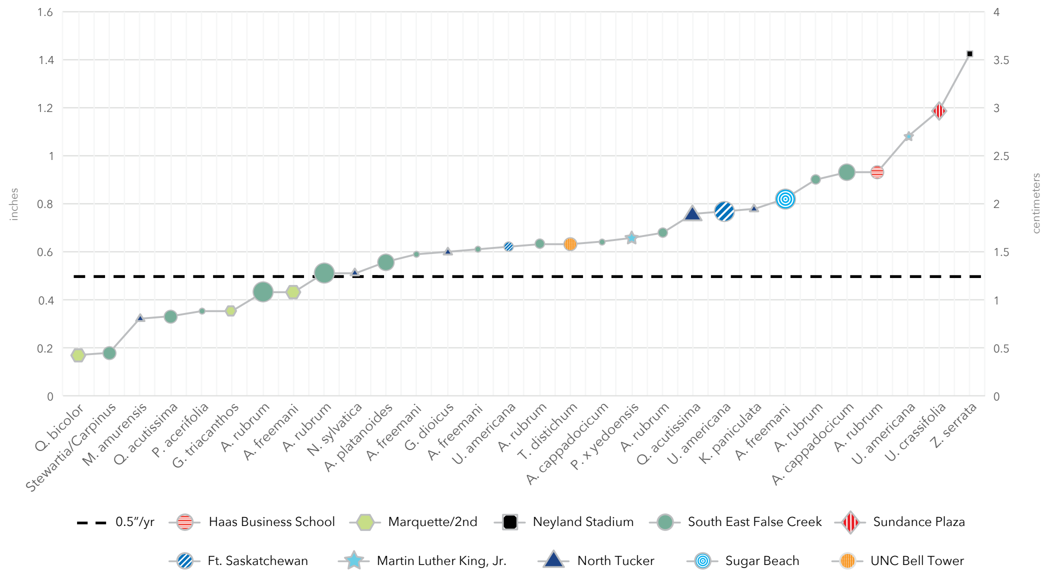


ANNUAL TRUNK DIAMETER INCREASE	# OF TREES IN SAMPLE	% OF TOTAL
Above 1.0” (2.54 cm) / year	46	11%
0.8 – 0.99” (2.03 to 2.51 cm) / year	73	18%
0.6 – 0.79” (1.52 to 2.00 cm) / year	98	24%
0.5 – 0.59” (1.27 to 1.49 cm) / year	60	15%
0.4 – 0.49” (1.01 to 1.24 cm) / year	46	11%
0.3 – 0.39” (0.76 cm to 0.99 cm) / year	29	7%
Less than 0.29” (0.73 cm) / year	40	10%
No growth measured (dead)	16	4%
Total	408	100%

GROWTH BY PROJECT

The following graph identifies each data set by its species and project name and is provided for reference purposes only. There are no conclusions that can be drawn from this information. Further conclusions in this study may occasionally use site names indicated on this graph.

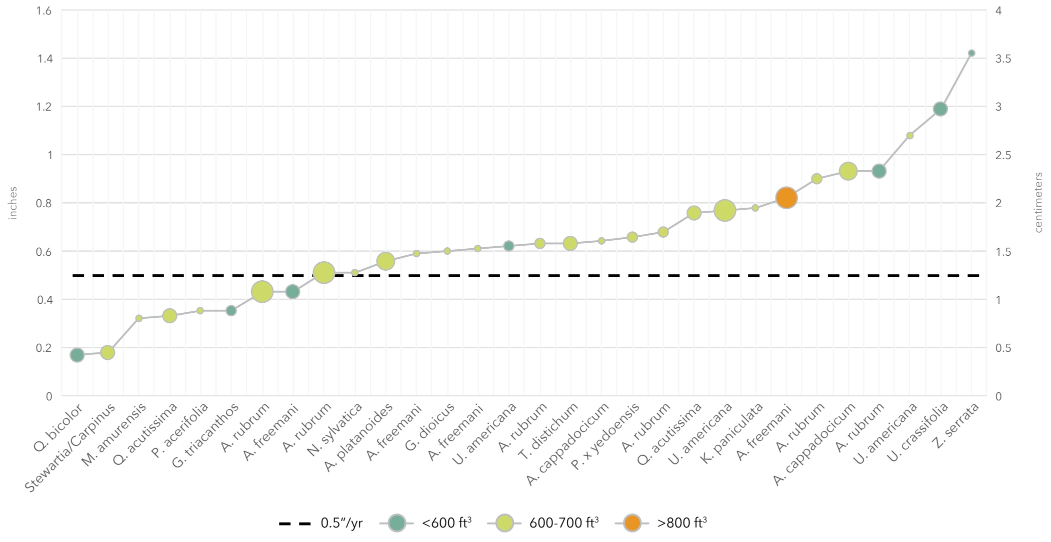
ANNUAL TRUNK DIAMETER INCREASE BY PROJECT



GROWTH BY SOIL VOLUME

In the early stages of growth the actual soil volume does not seem to be a factor in growth rate. This is a predictable result as not until the tree grows to its soil volume limitation should we start to see a significant difference in health and growth. Soil type and compaction may be a more significant factor than soil volume in the early years of a tree's growth as was seen in Smiley's study of different soil types and compaction (Smiley 2016).

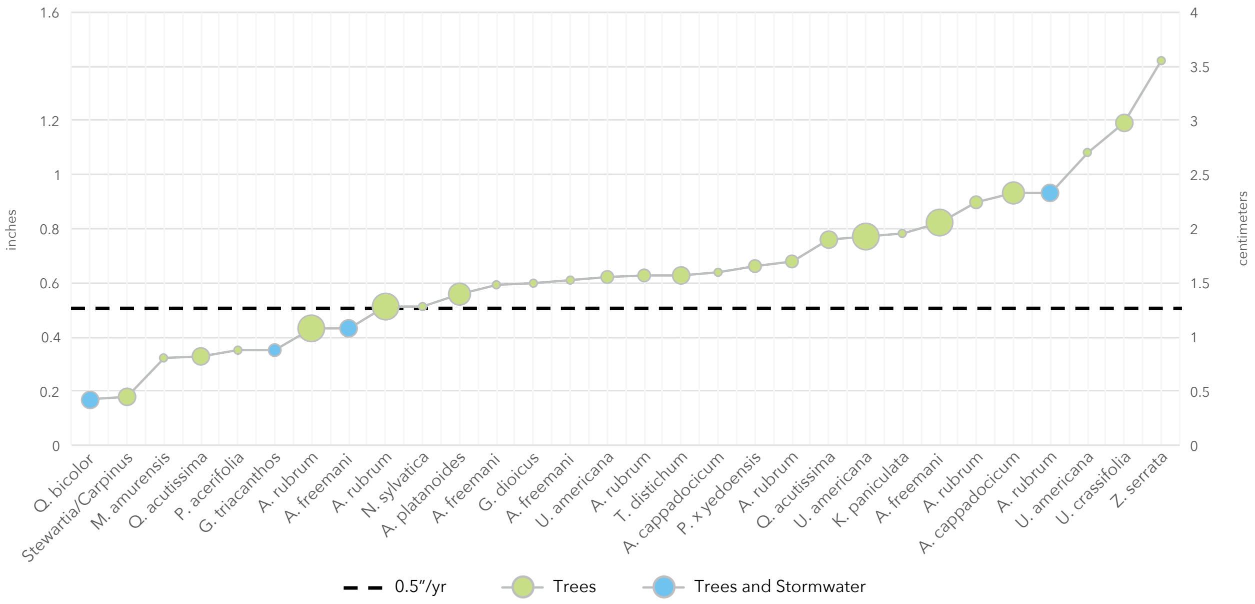
ANNUAL TRUNK DIAMETER INCREASE BY SOIL VOLUME



GROWTH BY INCORPORATION OF STORMWATER

An initial review of the data may seem to indicate that including stormwater does not favorably improve tree growth rates. This is a surprise. But the number of stormwater projects (2) is too small to be significant or to draw any conclusions. The trees on the larger of the two stormwater sites, Marquette and 2nd in Minnesota, had an average growth rate of less than 0.5 inches (1.27 cm) per year. On the other hand, the smaller number of trees at the Haas Business School in California were growing at over 0.9 inches (2.28 cm) per year. Additional research is continuing at Marquette and 2nd to determine what might be the reason for the slower growth; preliminary findings suggest that severe girdling roots are present on all the trees. Factors such as climate, location, street trees versus plaza trees, species, ice melt salt and lack of salt, and design of larger and smaller space around the tree are all easily identified differences between the two projects that might override the stormwater question.

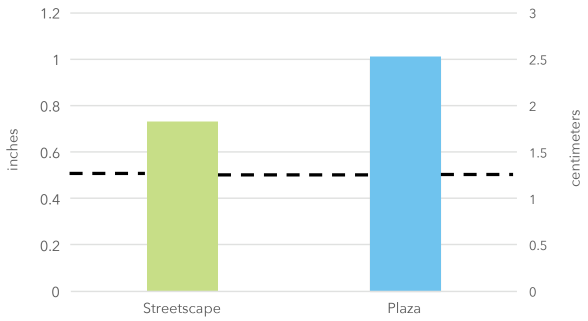
ANNUAL TRUNK DIAMETER INCREASE BY INCORPORATION OF STORMWATER



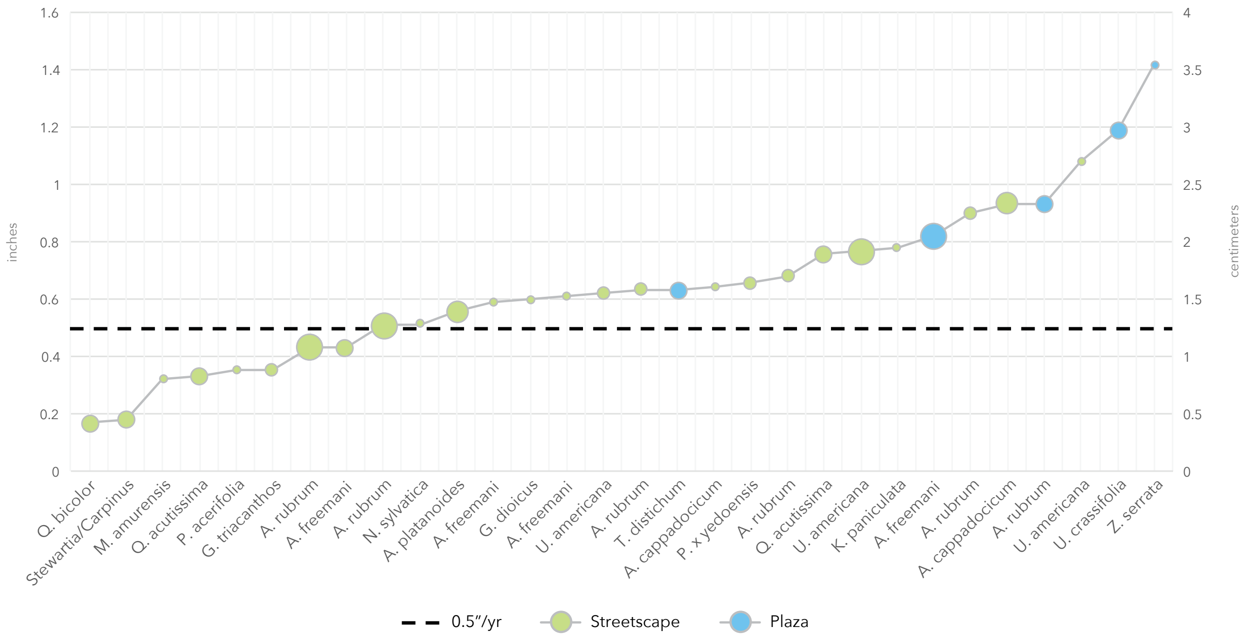
GROWTH BY SITE TYPE

While all sites performed well, street trees underperformed trees in plazas and spaces not on the street. This is not a surprise, as streets are a much tougher environment for trees. Street trees are often installed as part of a larger public works project, and follow-up maintenance and after care is less reliable. Plaza and promenade projects (such as Sugar Beach or Haas School of Business) are more often managed by a private or semi-public organization that takes greater care of the trees during and after construction.

ANNUAL TRUNK DIAMETER INCREASE BY SITE TYPE



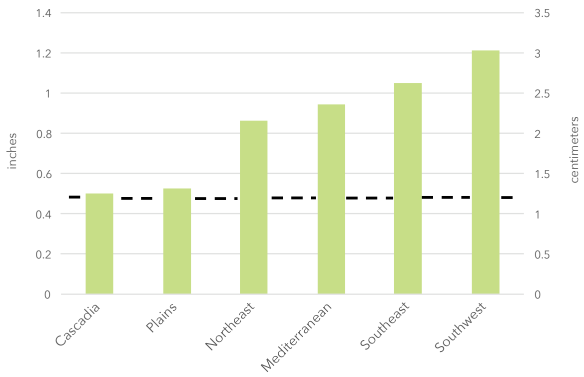
ANNUAL TRUNK DIAMETER INCREASE BY SITE TYPE



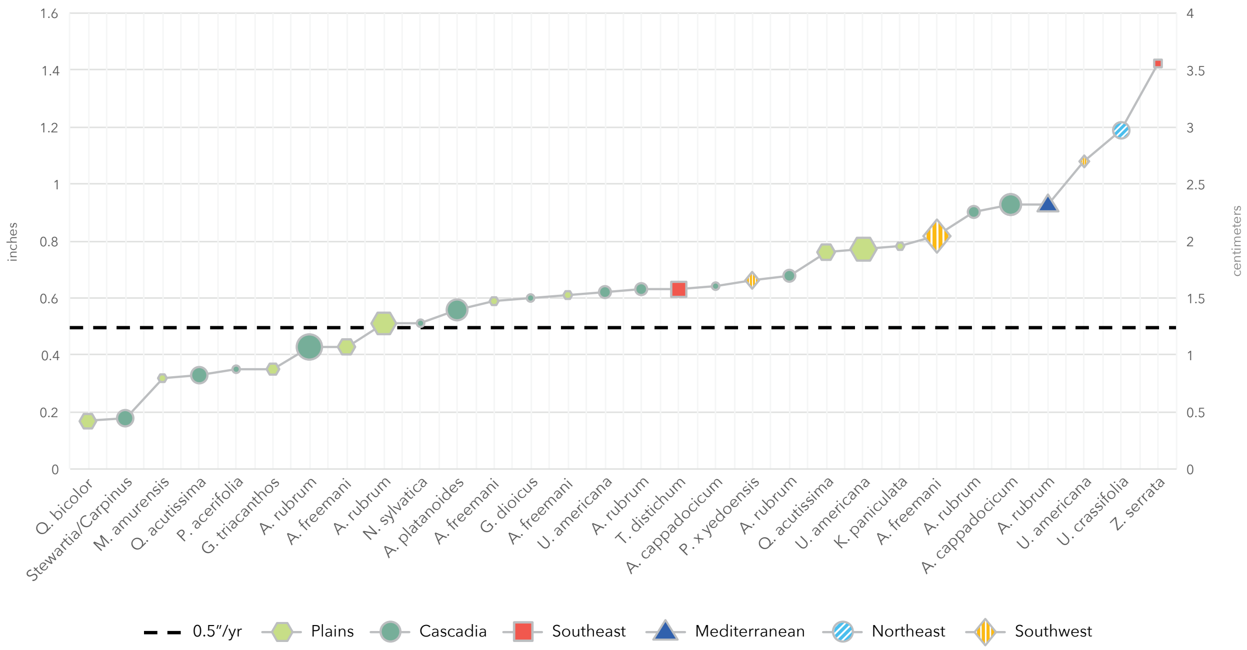
GROWTH BY REGION

While there appears to be a strong trend favoring some climate regions as better or worse, the samples sizes in some regions were quite small. For example, the single data sets in the Southwest and Mediterranean regions make the strong performance at these two projects statistically insignificant.

ANNUAL TRUNK DIAMETER INCREASE AVERAGES BY REGION



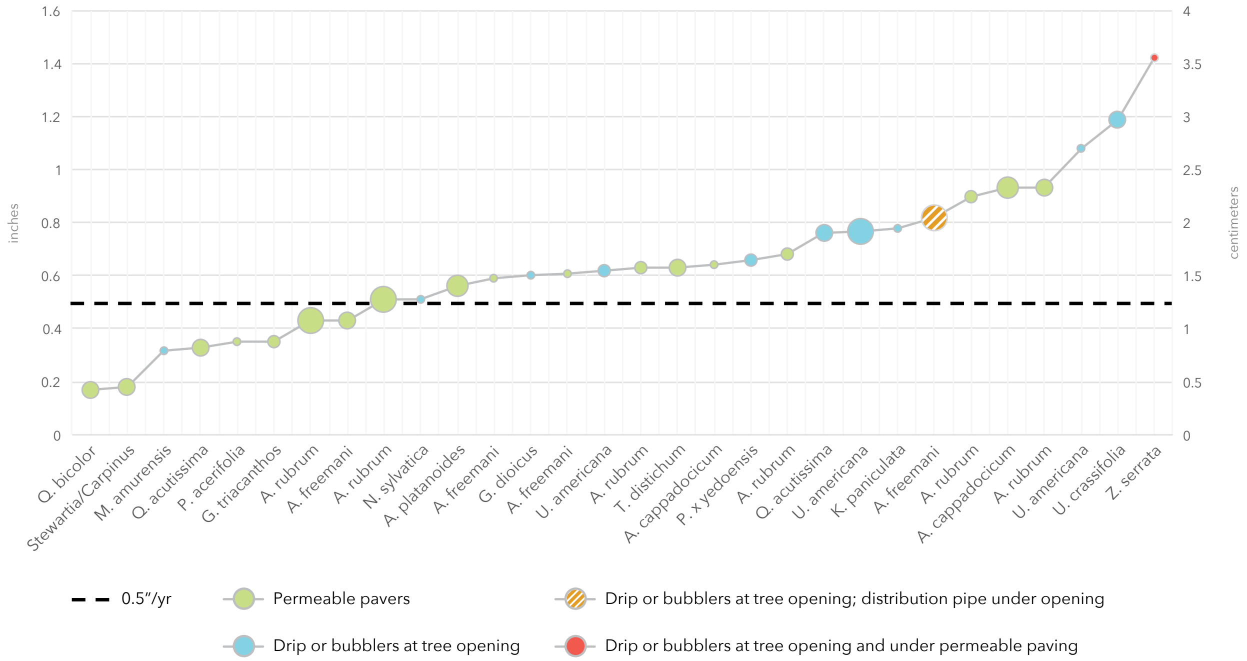
ANNUAL TRUNK DIAMETER INCREASE BY REGION



GROWTH BY IRRIGATION TYPE

The data from these projects doesn't show a strong relationship between different watering options and tree performance. Projects with drip or bubblers at the tree opening did seem to perform better overall, as did drip or bubblers at tree opening with a distribution pipe below the paving, although the latter was only present at one project. The trees at parts of South East False Creek (Vancouver, BC), some of which are underperforming, were in a section that had little access to water except small amounts of runoff from the adjacent pavers and hand watering during the establishment period. Better performing trees at SEFC had larger areas of pavement draining into the tree planting beds. Species choice likely also played a role in performance of the trees at this project. It's important to note that, while the trees at South East False Creek do not have any irrigation, in some cases tree openings included pavers with permeable joints, or were adjacent to irrigated flower beds. In addition, all trees at SEFC were hand-watered for the first two years after planting.

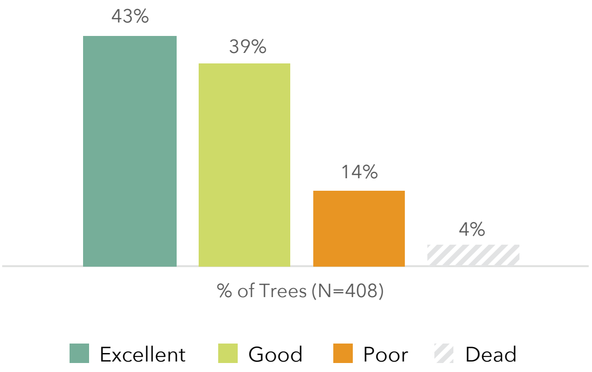
ANNUAL TRUNK DIAMETER INCREASE BY IRRIGATION TYPE



TREE CONDITION (OVERALL)

408 trees were given a visual assessment and rated on a scale of 1, 2, 3, or 4 according to guidelines described in the "Tree health condition" chart. The median tree condition for all project sites was either excellent (N=7) or good (N=3).

Projects ranged from an average rating of 1 ("Excellent: Good health, leaves dark green in color and fully covering the canopy") to 1.9 ("Good: Leaves lighter in color, significant leaf edge browning, not fully covering the canopy or some twig tip dieback. Damage to trunk or branches from impact"). The average health condition across all 10 projects was 1.4, indicating that the trees are in a healthy condition. Note that trees that were removed or dead are included here, but not in the rest of the study analysis, as their growth rate per year could not be measured.

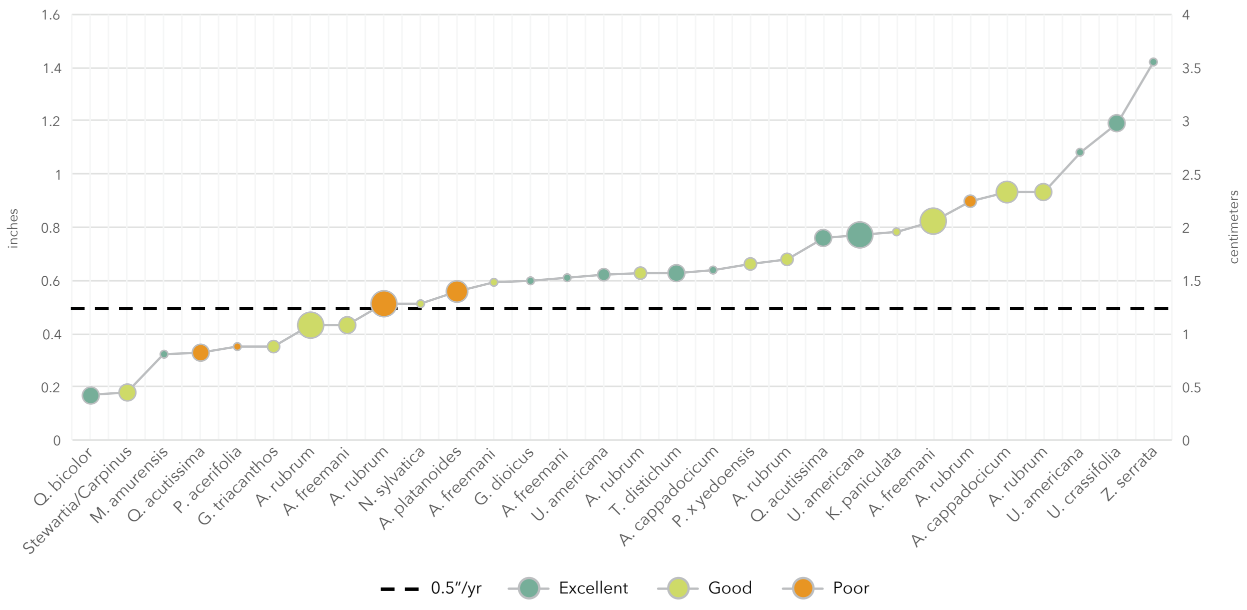


Tree condition scoring is significantly associated with average trunk growth per year, when controlling for type of tree species. On average the trees that were rated "good" grew 0.1 inches (0.25 cm) less than the trees in the "excellent" group (P=0.003), and trees in the "poor" group grew 0.2 inches (0.50 cm) less than those in the "excellent" group (P<0.001).

There is a statistically significant correlation between the trunk growth per year and tree condition ratings (R=0.35; P<0.001).

TREE CONDITION (BY SPECIES)

ANNUAL TRUNK DIAMETER INCREASE BY TREE CONDITION



DISCUSSION

This study looks at a large number of trees spread over 10 projects. Studies of trees in the public landscape have the issue of significant background influences and unknown problems that can impair tree growth and health. For example, contractors rarely follow all the project specifications and details to the letter, and conditions discovered during installation may cause some trees in any project to have slightly or even significantly different soil, watering, and/or drainage conditions. Issues with nursery stock quality are often not known or resolved. Irrigation may not function as planned. Some trees in the planting may suffer from damage caused by humans, dog urine, mechanical damage, or deicing salts. It is often difficult to determine if these influences occurred, and even harder to determine their impact on the outcome. However, nearly all public tree plantings suffer from the same types of problems, therefore understanding how trees planted in Silva Cells may perform against other options in these conditions is an important undertaking.

The standard deviation bars tell an important part of this story. Shorter bars mean the data is well grouped and typically found in controlled research sites, while longer bars indicate the average reflects a significant range in the data and less confidence in the results. The large variation in the data's standard deviation reflects a study of real-world constructed and accessible sites with significant variation of stress factors from project to project, and tree to tree, within any given project. By making the study large enough, with sites spread over a variety of regional and site types, the intent is to balance the background influences to determine tree performance under real world conditions.

The results of this study support the thesis that larger volumes of healthy soil make trees better able to thrive in these difficult locations. The study also shows that the use of Silva Cells alone will not assure healthy trees and that the project design must solve the entire set of problems that beset urban trees to give them the best chance of thriving into maturity.

Trunk diameter increase per year was used as the primary measuring point in the study. This is considered a reasonable indicator of tree health over time and reflects when a tree has recovered from transplant shock, or has experienced a severe stress. Trunk diameter is the easiest and most accurate metric to determine and is easily replicated over many sites by different recorders and over time as the study moves forward. Its importance is then balanced by looking at the other metrics and factors that influence tree growth.

The study set a bar of 0.5 inches (1.27 cm) of trunk diameter increase per year as a baseline for comparison. This rate of growth is considered to reflect reasonably good growth in the urban forest for street trees. Trees that grew at or above 0.5 inches (1.27 cm) per year were considered well-performing, and trees that grew above 0.8 inches (2.03 cm) per year were considered exceptionally healthy. Trees that are growing slower than 0.5 inches a year are not automatically in poor health. But as growth rates slow they indicate that there are beginning to be some influences that impact the tree growth. These may include factors such as a slower growing species, too little water, too much water, low soil fertility, or low light levels.

Trees that grew between 0.4 inches and 0.5 inches (1.01 and 1.27 cm) were considered healthy and to be growing at a reasonable rate depending on species and climate. Trees that grew between 0.3 inches and 0.4 inches (0.76 and 1.01 cm) we considered to be growing slowly, but still fast enough to remain viable. Trees that grew between 0.2 inches and 0.3 inches (0.50 and 0.76 cm) we considered slow growing, and would benefit from investigation into the cause of the slow growth. Finally, trees that grew at or below 0.2 inches (0.50 cm) were considered to have very slow growth that may indicate future decline.

68% of the total number of trees in this study had 0.5 inches (1.27 cm) or more of annual trunk diameter increase, the reference growth rate for normal, healthy street trees. 29% of those were above 0.8 inches (2.03 cm) of trunk diameter increase. 32% of the total number of trees had less than 0.5 inches (1.27 cm) of annual trunk growth. 11%, or about one third of the slower trees, were growing between 0.4 inches (1.01 cm) and 0.5 inches (1.27 cm) annually, which is below the reference level used here, but still a healthy growth. 14% had less than 0.29 (0.73 cm) of annual trunk growth. Two replacement trees were included in average growth rate calculations.

It is important to consider if faster tree growth rates are actually desirable. While a faster growing tree usually reflects better growing conditions, faster growth does not translate into longer-lived trees. Wood is not as strong and some disease vectors, particularly some leaf feeding insect activity, may be increased on softer leaf tissue. Pruning cycles are more frequent and the tree may exceed its space faster.

On the other hand, a faster growing tree typically recovers from mechanical damage and has better resources to withstand multiple stress factors. The faster growing tree will gradually slow its growth as it becomes in competition for light and water. Further research on this issue may benefit not only the understanding of tree in soils below pavement, but wider urban forestry concerns.

Only three genera, Quercus, Acer, and Ulmus, have enough replicates to make observations of trends in trunk diameter increase by tree type. Acer has the largest number of data sets (13) and this genus performed well, most above 0.5 inches (1.27 cm) per year and two sets just below 0.5 inches (1.27 cm). While Acer is often used as an urban tree, it also has had performance problems as a street tree. Ulmus, with four data sets, is the best performer – this is not surprising as it is typically a very good urban tree. Quercus has only three data sets, and two are underperforming. Again, this is not too surprising as this genus is often hard to establish. The remaining sets of trees include eleven different genera, each in only one location, somewhat randomly spread over the breadth of the growth rates. Five of the eleven grew less than 0.4 inches (1.01 cm) per year. Of that group three tree types, Maackia amurensis, Carpinus caroliniana and Stewartia spp., are very slow growing even in good soil conditions and should be considered as growing reasonably normally. It is likely that tree type is not particularly critical to the success of the system, but also indicates that more research might provide a better understanding of tree selection to the overall success of the approach.

Trunk diameter increase by irrigation type did not reveal a strong trend. While nearly all trees with "drip or bubblers at tree opening" saw over 0.5 inches (1.27 cm) of annual growth, and trees with permeable pavers were distributed both above and below the 0.5 inch line, the sample size (number of trees) of those with "drip or bubblers at tree opening" was significantly smaller. Similarly, while the "drip at bubblers at tree opening; distribution pipe under opening" and "drip or bubblers at tree opening and under permeable paving" trees all appeared to have 0.8 inches (2.03 cm) annual growth or greater, the total number of trees meeting each condition was small, from a single project, and therefore not statistically significant.

Trunk diameter increase by incorporation of stormwater is an area that could use further study. There were two projects that explicitly incorporated stormwater into the designs, Haas School of Business (Berkeley, CA) and Marquette and 2nd (Minneapolis, MN). We examined the soil specifications for both and found that neither is a high sand bioretention mix, meaning they are more friendly to plant needs. We expect both soils to function well for rain water treatment, and have every indication that the systems are functioning as designed. Yet the trees at one project (Haas) are seeing high annual trunk growth, and some trees at the other (Marquette and 2nd) were underperforming. Based on our analysis we feel confident saying that the soil did not negatively impact tree growth.

Given the climate difference between California and Minnesota, it is likely that climate was a more significant factor in these two sets of trees. The Haas trees (Berkeley, CA) would likely benefit from an increase in water while the Marquette and 2nd trees (Minneapolis, MN) might not grow better as there is generally more rain in that drier climate. The excess water collection in Minnesota might be too much water, and/or the water in winter might have significant salt concentrations that would not be present in the California location. A preliminary study of the Marquette and 2nd project revealed severe girdling roots on all the studied trees, which likely accounts for their uneven performance — and bodes poorly for their long-term survival.

Trunk diameter increase by soil volume saw no strong trend line as all the projects had sufficiently large enough soil volume to assure good establishment, and no trees were old enough or large enough to be impacted by low soil volumes. We would expect the limitations of the soil volume to start presenting themselves in the growth and vigor of the trees starting around year 20 or 30 for those trees with the least soil.

Trunk diameter increase by site type — street trees or plaza trees — indicated that plaza trees performed significantly better overall. This was not a surprise as plaza trees typically get better maintenance and are stressed less by vehicle and pedestrian abuse than street trees. In northern climates street trees are also subjected to significantly more salt stress than plaza trees.

Trunk diameter increase by region does not reveal a trend that it is any harder or easier to grow trees in Silva Cells in different climates. It may be that trees in the driest climates receive extra irrigation to compensate for the harsher conditions. Overall, there were not enough data sets in each region to draw any broad conclusions.

Distribution of tree condition rating indicates that trees generally are very healthy in Silva Cells. 43% of the trees were in excellent condition with another 39% in good condition. 14% were in poor condition. Only 4% of the trees were dead or replaced.

CONCLUSIONS

Based on the data from the above projects, it appears that trees growing in Silva Cells perform very well in terms of visual health indicators and annual growth. 82% of trees in the study were given a health rating of either "excellent" or "good." This is especially notable given the large sample size, the variety of species, climates, and maintenance regimes, and the difficult conditions faced by urban trees.

Silva Cells primarily serve to protect soil from compaction, a major constraint to tree growth as indicated by Coder (2007). This study shows that Silva Cells improve tree performance in urban areas across a wide range of climates, regions, and tree species.

The trees that are growing at rates well above (greater than 1"/2.5cm per year) and below (less than 0.3"/0.76cm per year) the normal range of healthy trees require further investigation to see how changes in the design of the system, or maintenance or water regimes, may be impacting the growth positively or negatively. The details of the designs and specifications should be reviewed and compared. The trees growing in excess of 1 inch (2.5 cm) per year should be followed to see if this rapid growth introduces any management problems.

The study suggests that some additional projects that are designed for stormwater might be added to look more closely at the relationship to soil type and water access, water treatment performance, clogging and maintenance, and other design differences.

This set of well documented trees is an excellent base to examine tree performance in the future as the trees grow. A follow-up study would be appropriate in three to five years.

Since this study was undertaken with trees in public environments, there are undoubtedly challenges and abuses to the trees that influence the results and future performance of the trees. The performance metrics found in this study should not be used to predict outcomes of other sets of trees, as it is likely impossible to duplicate the factors that determined growth rates in any individual, group, or region.

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James Urban, FASLA, is the founder and sole owner of Urban Trees + Soils, a design firm that provides consulting services to landscape architecture and architectural firms in the area of urban trees, urban soils, and large tree preservation. He was part of the original Silva Cell design team and has been an integral part of the DeepRoot team as a consultant. He is one of the named inventors on the Silva Cell patent.

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COLLABORATORS

The following is a complete list of collaborators, including a brief summary of their qualifications. These people contributed their time and expertise to the measurement and assessment of the trees included in this study.

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Lisa Clearwater. (Sherwood Park, AB). *Lisa is an ISA-certified arborist.*

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LITERATURE CITED

Bassuk, N. Loh, F. Grabowsky, J. "Growth Response of Ficus benjamamina to Limited Soil Volume and Soil Dilution in a Skeletal Soil Container Study." Urban Forestry & Urban Greening 2 (2003): 053-062.

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

City of Toronto, Ontario, Canada, "Tree Planting Standards for Hard Boulevard Surfaces - Best Practices Manual" (2012).

City of Stockholm, Sweden. "Planting Beds in the City, GH100322." (2009).

Coder, Kim D. "Soil Compaction, Stress and Trees: Symptoms, Measures, Treatments." University Of Georgia Warnell School Of Forestry & Natural Resources. Warnell School Outreach Monograph WSFNR07-9 (2007).

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

Layman, R.L., S.D. Day, D.K. Mitchell, Y. Chen, J.R. Harris, and W.L. Daniels. "Below ground matters: Urban soil rehabilitation increases tree canopy and speeds establishment." Urban Forestry & Urban Greening. (2016): 25-35.

Perry, T. "Trees and their Typical Ages and Growth Rates." Metropolitan Tree Improvement Alliance Proceedings 1 (1978).

Rahman, M., Stringer, P., Ennos, A. "Effect of Pit Design and Soil Composition on Performance of Pyrus calleryana Street Trees in the Establishment Period" Arboriculture & Urban Forestry 39(6): (2013).

Smiley, T. Urban, J. "Evolution of Established Trees in Structural Soils and Suspended Pavement." International Society of Arboriculture Annual Meeting, Milwaukee, WI (2014).

Smiley, T. "Soil Under Pavement Study, Four Approaches and Three Control Plots - On Going Research." Personal Communication (2016).

Smiley, T. Calfee, L. Fraedrich, B. Smiley, E. "Comparison of Structural and Non Compacted Soil for Trees Surrounded by Pavement." Arboriculture & Urban Forestry 32 (2006) and ongoing observations of plots. Personal communication (2007 to 2016).

Teck, R. Hilt, D. "Individual-Tree Diameter Growth Model for the Northeastern United States." USDA Forest Service Research Paper NE-649 (1991).

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