EVALUATION OF SOIL VOLUME REQUIREMENTS FOR URBAN TREES

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ABSTRACT

Urban trees provide a plethora of benefits when they are able to grow strong and healthy canopies. There is widespread acceptance that limited soil volume is responsible for reduced urban tree vigor and thus performance. However, little research has been conducted to determine adequate soil volumes for street trees. Several municipalities have minimum soil volume requirements, though these requirements are not scientifically derived and are highly variable. One commonly used method for calculating soil volume requirements for urban trees in the Lindsey/Bassuk method, which estimates daily water use and specifies a soil volume large enough to store enough available water to sustain a tree during rain-free periods. This research tested the ability of Lindsey/Bassuk to predict occupied soil volumes for twelve established Red Maples. We found that Lindsey/Bassuk consistently underestimated the occupied volume by, on average, 47%. We modified several parameters in the model in an attempt to reduce that error and produce more reliable estimations of occupied soil volume. By accounting for estimated turf water use and by specifying site-specific soil parameters, we were able to reduce the underestimation of occupied soil volume to a mean error of 13.8%. More research is necessary to further quantify soil volume requirements for urban trees. Our study, with its small sample size, provides direction for future research.

BIOGRAPHICAL SKETCH

The author was born and raised in Syracuse, New York. During high school and college, he worked as a seasonal penguin keeper at the Rosamond Gifford Zoo in Syracuse, where he developed a love for the mysteries of the natural world and an interest in how people think about science and the environment. Patrick attended Cornell University, majoring in Animal Science with a minor in American Indian Studies. After graduating, he joined the Urban Horticulture Institute as the research technician, managing several research projects and garden landscapes. In 2011, he was admitted into the graduate program to pursue a Master's Degree under the tutelage of his advisor, Dr. Nina Bassuk. He continued to work as the Urban Horticulture Institute technician throughout his studies, and he maintains that position to date. Outside of academia, Patrick's interests and hobbies include gardening, hiking and woodworking; activities that he's pursued as he has built his home in Spafford, New York.

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CHAPTER I

INTRODUCTION AND BACKGROUND

Tree roots, while notoriously difficult to study, are critically important to understand. There is widespread acceptance in urban forestry literature that without achieving adequate crown dimensions, the ecosystem services provided by trees are limited. Municipalities are increasingly characterizing street trees in terms of the ecosystem services they provide in order to advance their urban forestry agendas (Seamans, 2013). However, without adequate usable rooting volumes, it is unlikely that trees will achieve their intended size and potential and contribute the benefits expected of them. Several authors have investigated the effect of designed space on ultimate tree size (Sanders et. al, 2013, Day & Amateis, 2011). Kim (2012) suggests that limited above and below ground space has led to a disproportionately young, small street tree population in Hong Kong, despite a continuous tree planting program dating back over 150 years. The author also suggests that because of the lack of space dedicated to tree planting areas, the current tree population in the city has little potential to mature. Limited rooting volume is a major reason why trees in urban environments fail to develop the canopies that would allow them to contribute to the plethora of benefits offered by healthy, vigorous canopies. Thus it is important to expand the current understanding of the volume of soil required to support trees of a given envisioned size. Several municipalities across the United States have developed minimum soil volume requirements for new tree plantings. According to the green infrastructure blog deeproot.com, these guidelines are highly variable, ranging from 19.9 m3 (700 ft^3) for large trees in Durham, NC to 76.5 m^3 (2,700 ft^3) in Florida.

Little research has been conducted to quantify the effects of limited soil volume on urban trees or on the volume of soil necessary to support adequate tree growth and vigor, though there is

widespread acceptance of the positive correlation between increasing soil volume and increased canopy size in the urban forestry profession. Further, those investigations that have established the connection between increasing designed size and increasing tree size suggest the same relationship to soil volume. Boland et. al. (1994) investigated the effects of limited soil volumes on peach trees and discovered that reducing soil volumes resulted in reduced water consumption, reduced canopy volume and increased yield. While urban forestry professionals are unconcerned about yield, reduced canopy volume is not a desirable outcome in urban forest management. Lindsey & Bassuk (1991) developed a model for calculating the volume of soil required to support street trees (figure 1). Their model was based on mathematical calculations of the effect of evaporative demand on whole-tree water use. Empirical studies to support the calculations were confined to small, containerized trees. Since the time of that publication, little further research has been conducted investigating the accuracy of their recommendations or about urban tree soil requirements in general.

Step 1- Determine Daily Water Use:

Crown Projections x LAI x Highest mean daily evaporation (July) x .2 correction factor = Daily Water Use

Step 2- Determine Soil Volume Required to Retain Moisture to Meet Water Use Over Rain-Free Interval

(Daily Water Use / AWHC) x Precipitation Interval = Soil Requirement

Figure 1- The Lindsey Bassuk Model for Soil Volume Recommendations

Modern technologies are making root investigations more attainable, and it is highly likely that as technology evolves, more studies will be undertaken to investigate tree roots and their associated soil volumes. Ground-penetrating radar and pulse tomography are such technologies that have been employed by the author and Cornell's Urban Horticulture Institute (data

forthcoming), among others (Bassuk et. al., 2011; Butnor et. al., 2001; Jan et. al. 2013). The benefit of GPR is that it is a completely non-invasive method that can reliably locate tree roots under certain soil conditions. There is a need for additional ground-truthing studies before conclusions may be made about the ability of radar to identify tree roots in wide-ranging soil conditions. Those studies are necessary before the technology can be incorporated into non ground-truthed studies that require detailed and precise information about the distribution of roots. As such, there is still a need for invasive root investigations when such information is required. This study is one such project. The objectives of the research were to test Lindsey/Bassuk soil volume recommendations on existing trees ranging in size from small trees planted within the past five years to large, mature trees. Our aim was to determine if the Lindsey Bassuk model accurately predicted the volume of soil occupied by each of the trees. Typically, Lindsey/Bassuk is used to calculate recommended soil volumes for trees during the landscape design phase (before tree installation). Planners, designers and landscape architects use the model to incorporate appropriately sized tree planting areas into their projects based on the envisioned mature canopy size. This study worked the model backwards. For trees with known canopy sizes, what soil volume would have been recommended by Lindsey/Bassuk? Is that volume close to the actual volume occupied by the root system of those trees? If not, can the model be altered to result in a more reliable model?

Our objective was to calculate Lindsey/Bassuk recommendations for existing trees of variable size and compare the recommendations to the soil volume actually occupied by those trees. If the model recommendations disagreed with the occupied soil volumes, a second objective was to determine the cause of the discrepancy and determine methods to reduce the error.

The Lindsey/Bassuk (LB) model has never been tested on existing trees. Several components of the model rely on assumptions that may lead to over- or under-estimations of occupied soil volume. The LB methodology relies on a series of assumptions. First, the model assumed that street trees must have 100% of their water needs met throughout the growing season. While the scientific understanding of water use in urban trees is limited, it is known that trees can maintain efficient stomatal control and thus regulate water use based on available soil water (Lediavilla and Escudero, 2004). It is unclear from the literature how much water stress a tree can endure while maintaining its basic functionality. The LB model estimates whole-tree daily water use by multiplying the crown projection by leaf area index and a proportion (a correction factor of .2) of the highest mean daily evaporation, obtained from Class A Evaporation Pan data. At their study site in Ithaca New York, the highest evaporative demand occured in July.

CP x LAI x Highest mean daily evaporation (July) x .2 = Daily Water Use

As a result of using the highest mean daily evaporative demand figure, the resulting estimation of daily whole-tree water use is inflated when projected across the growing season. It would stand to reason that daily water use at other points in the season with lower atmospheric demand would be reduced. Since the LB model recommends soil volumes which would be able to store enough moisture to support a tree's *full* estimated water use as calculated for the hottest and driest period during the season and assumes that same demand across the growing season, intuitively one would assume that the model over-estimates the necessary storage capacity for less intensive periods of transpiration. A logical conclusion may be drawn that the potentially over-estimated water use may result in exaggerated soil volume recommendations. Further, because the model provides enough storage capacity to meet 100% of the tree's estimated water needs at all times, it

is likely that the recommendations are more liberal than is actually necessary to support the most basic needs of the tree, assuming it is asserting stomatal control over transpiration.

Following their estimation for daily whole-tree water loss, the LB model calculates a soil volume necessary to store enough moisture to meet the water needs of the tree between precipitation events.

(Daily Water Use / AWHC) x Precipitation Interval = Soil Requirement

LB incorporates an interval of ten days between what they consider to be critical precipitation events of 1/10th of an inch or more. This amount of rainfall is accepted as significant enough to provide some soil water recharge. The ten day interval was chosen for the LB model under the assumptions "1) that sufficient soil water storage occurs from November to April so that the soil is fully recharged in May and 2) the calculated soil volume would hold sufficient water to carry the tree through the interval chosen, after which recharge of soil water would occur through precipitation, the water table, lateral water movement, or perhaps irrigation".

The first assumption of LB may result in overestimations of soil volume requirements. The second assumption may result in underestimations. To this point, it is unknown whether those assumptions would cancel each other out, thus leading to reasonably accurate recommendations, or whether the magnitude of one assumption would pull the recommendation in one direction and lead to either too large or too small recommendations. We determined that it would be of practical utility to test the LB soil volume calculation on existing trees. Trees of the same species and of various sizes were selected for the study, and their root systems were excavated to determine the occupied soil volume. We then compared the occupied soil volume to the volume

that LB would have recommended, given the size of each tree's canopy. The model was then altered to reduce the error between the calculated volume and the occupied soil volume.

CHAPTER II

MATERIALS AND METHODS

Plant Material- In October 2011, twelve Red Maples (*Acer rubrum*) were selected for this study. Plants were selected that represented a range of sizes. Chosen plants were required to meet several selection criteria. First, they had to be clearly identifiable as Red Maple. Second, they had to have been established at their current location for a minimum of three growing seasons. This time period would allow us to reasonably assume that they had recovered from any transplant shock and had resumed typical growth. Third, the trees had to be relatively open-grown. Trees were considered open-grown if there were no other trees growing within their immediate vicinity. Initially, we conducted a search for trees growing alone in open fields. Locations were scouted in and around Ithaca, NY. Due to the paucity of open-grown Red Maples that met our criteria, we were unable to select truly open-grown trees. Instead, trees were selected that were not growing in a wooded environment, had no woody plants growing within fifteen feet of their canopy dripline, and had at least ½ of the circumference of the dripline clear of trees for an extended distance. That distance varied based on the size of the tree.

The twelve trees that met all of our selection criteria and ultimately made it into our study are part of the Cornell Plantations Maple collection. These trees have the tremendous advantage of having an exhaustive inventory record cataloguing their accession date, species and maintenance history. The Cornell Plantations is located in Ithaca, NY, adjacent to the Cornell University campus. The arboretum is in USDA Hardiness Zone 5B.

Once the trees were selected, we collected various size measurements for each tree. Diameter at breast height (DBH) was measured using a standard diameter tape at a height of 1.37 meters (4.5 feet). On low-branched trees, the DBH was taken beneath the taper of the lowest branch, as per

the American Nursery and Landscape Association American Standards for Nursery Stock (ANSI Z60.1-2004). Crown dimensions (height, width and depth) were measured using a LaserAce™ 1000 Rangefinder (Trimble Navigation Limited; Sunnyvale, California). Width and depth were measured at the bottom of the crown and crown height was measured from the bottom of the live crown to the top of the live crown, along the centerline of the tree. Each dimension was measured twice, and the values were averaged, yielding *average width, average height* and *average depth*. This was done to control for user-based variability in the measurements. The average depth and average width were measure at zero and ninety degrees. To calculate crown projection, the average width and average depth of the crown were averaged and treated as the mean crown diameter. Crown radius was calculated by dividing the crown diameter by 2. Area under the dripline (syn. Crown Projection) was calculated by incorporating the average crown radius into the formula $A=\pi r^2$. Canopy Volume was calculated by multiplying the Crown Projection by the *average height*. Tree dimensions can be found in Figures 2.

Tree Number	Mean Tree Height (m)	Mean Height to Live Crown (m)	Mean Height of Live Crown (m)	Mean Width (m)	Mean Depth (m)	Mean CP (m^2)	Mean Crown Volume (m^3)	DBH (cm)
1	6.78	1.34	5.44	4.98	23.75	29.33	196.27	13.72
2	8.67	1.20	7.47	6.37	23.50	35.96	341.09	24.38
3	9.9	1.21	8.69	7.30	24.45	42.73	472.99	30.99
4	3.04	1.83	1.22	2.44	8.00	4.67	7.25	6.35
5	4.63	1.40	3.24	3.00	9.45	6.79	28.01	6.10
6	10.82	0.72	10.11	11.11	32.90	87.73	1126.54	31.50
7	7.34	1.12	6.22	4.65	17.05	19.03	150.38	13.72
8	7.6	0.90	6.71	6.13	26.60	39.78	333.08	21.59
9	6.88	1.26	5.62	4.80	12.55	14.61	103.27	13.72
10	5.97	0.87	5.11	8.18	14.85	31.72	189.12	14.99
11	5.91	0.67	5.24	5.72	14.30	19.93	130.59	16.00
12	4.77	0.42	4.36	6.80	17.05	28.25	153.96	11.43

Figure 2- Tree dimensions for all 12 experimental Red Maple trees

Site History- The Cornell Plantations Arboretum (42°27’5.68”N, 76°27’20.61”W) is a 100 acre site situated in a natural bowl that was created by alluvial sculpting following the retreat of the Laurentide ice sheet during the Wisconsin Episode. Before the site became an arboretum in

1982, it was used as pasture for beef cattle. The Red Maples in this study are located at the base of a slope that passively directs runoff to the area in which the trees are growing. Three artificial ponds were constructed on the site in 1986, before the trees in this study were planted. The ponds were designed to capture and hold the runoff water coming off the slope. When the ponds were dug, the excavated materials were spread across the site. As such, the assumption was made that the soil conditions were relatively homogenous across the entirety of the area in which the trees in this study are growing. That assumption was tested through comprehensive soil sampling.

Soil Sampling- In the spring of 2013, soil samples were collected for analysis of Available Water-Holding Capacity. Samples were collected in the top 15.24 centimeters of the soil profile at two depths: Surface (0cm)-7.62cm (0-3 inches) and 7.62cm-15.24cm (3-6 inches). These depths were chosen because, based on physical analysis of rooting depth, we knew that the majority of roots were located in the 0-15cm zone (figure 3). In each location where soil was to be collected, a 30cm^2 (12 in^2) square section of sod was removed using a sod knife and a flat shovel. To collect the surface-zone (0-7.62cm) samples, a steel soil corer measuring 5.08cm x 7.62cm (2 in x 3 in) was inserted into the soil column by placing a block of wood over the core and repeatedly tapping the block with a mallet until the top of the core was exactly at the soil surface. The core was then gently dug out of the soil profile and removed. Care was taken to ensure that no soil fell out of the core. The top and bottom of the core was trimmed of excess soil using a flat-edged knife. The soil was then removed from the core and put into a sealable plastic bag, labeled with the ID of the tree associated with that particular sample. To collect the 7.2-15.25cm soil samples, all soil in the 30cm^2 section was removed using a trowel to a depth of 7.62cm. The same procedure that was used for the surface layer sampling was repeated (thus, the "surface" was now at a depth of 7.62cm and the bottom of the core at a depth of 15.24cm). The

soil collected at this depth was added to the same bag as the surface layer sample. For each of the twelve trees in the study, an associated soil sample was collected that was an aggregate of the soil profile from the surface to 15.24cm. Soil samples were collected in two 'lifts', because the height of the soil core limited the depth to which a single sample could be taken.

Following collection of the aggregate soil samples for each of the twelve trees, samples were submitted to the Cornell Nutrient Analysis Laboratory for measurement of their Available Water-Holding Capacity. The laboratory followed a standard protocol for measuring gravimetric available Water-Holding Capacity. Small amounts of each sample were placed on ceramic plates in a high pressure chamber. Each sample was contained by a rubber ring. Water was extracted at field capacity (10 kPa) and at the permanent wilting point (1500 kPa). After the sample equilibrated, it was weighed and then oven-dried overnight at 105°C (221°F). The dried samples were weighed, and the soil water content at each pressure between field capacity and the permanent wilting point was calculated. The available water capacity is the weight of soil water lost between 10 and 1500 kPa.

Concurrent with soil core sampling, penetrometer depth measurements were collected adjacent to each core site (Dickey-John Soil Compaction Tester). The purpose of measuring penetrometer depth was to determine the depth at which root growth would be obstructed due to excessive soil compaction. Our aim was to determine the depth to which we should search for roots during the physical root measurement phase of the project. We operated under the assumption that root growth is restricted in soil with penetration resistance of 300 psi. Ten sites under the dripline of each tree were sampled and averaged. Results of the soil testing are presented in figure 3.

Tree Number	AWHC	Mean Penetrometer Depth (inches)	Mean Penetrometer Depth (cm)
1	0.30	5.7	14.48
2	0.32	6.2	15.75
3	0.33	4.6	11.68
4	0.29	6.1	15.49
5	0.32	4.8	12.19
6	0.33	5.3	13.46
7	0.33	6.2	15.75
8	0.32	5.4	13.72
9	0.36	5.7	14.48
10	0.35	6.5	16.51
11	0.31	7	17.78
12	0.30	5.8	14.73

Figure 3- Gravimetrically derived available water holding capacity and penetrometer depth at 30 PSI for each tree

Determination of Occupied Soil Volume- During the summer of 2012, we located and measured the extent of the root systems for each of the twelve trees in the study. Four trenches were air-excavated at 0, 90, 180 and 270 degrees around each tree using an Air-Spade 2000 Arbor/Landscape kit (Guardair Corporation, Chicopee, Ma). The proximal end of the 40.6cm (16 in) wide trenches began 1.22 meters (4 ft) from the trunk. First, turf was removed over each observation trench using a sod cutter set to a depth of 2.54 cm (1 in). This insured that the turf would be fully removed, while limiting the depth of the cut into the soil profile. Next, soil was removed from the trenches using the air excavation tool. Major rope-like roots were located as the soil was removed. We followed the length of the root using the air excavation tool until the root terminus was located. The length of the root systems was considered to be the length from the trunk to the root terminus for each trench. The lengths determined for each of the four trenches were averaged, yielding an average root length or *root extent*. The *root extent* was considered to be equivalent to the radius of the root system. Root system area (A_r) was calculated using the formula $A_r=\pi r^2$. Area was multiplied by 15.25 cm (6 in), the depth at which

penetrometer data suggested that roots would end, resulting in Occupied Root Volume (V_o). V_o values are presented in figure 4.

Tree Number	Mean trench Length (ft)	Mean Trench Length (m)	V_o (ft^3)	V_o (m^3)
1	13.56	4.13	288.79	8.18
2	17.38	5.30	473.97	13.42
3	24.75	7.54	961.72	27.23
4	5.38	1.64	45.36	1.28
5	7.75	2.36	94.30	2.67
6	21.75	6.63	742.71	21.03
7	16.63	5.07	433.93	12.29
8	21.00	6.40	692.37	19.61
9	12.13	3.70	230.81	6.54
10	19.50	5.94	596.99	16.90
11	14.33	4.37	322.55	9.13
12	14.67	4.47	337.72	9.56

Figure 4- Occupied root volumes (V_o)

<u>Lindsey-Bassuk Recommendation Calculations-</u> For each of the twelve study trees, the Lindsey/Bassuk model recommendations were obtained in a retrospective analysis. The measured crown projection was added into the model to determine the volume of soil that the model *would have* recommended for each one of the trees. The volume recommendations were derived using the same parameters established in the 1991 paper: A Leaf Area Index of 4, 19% AWHC, ten day precipitation interval and July Pan Evaporation data. Average Pan Evaporation for July was calculated for the years 1982-2012 to reflect any climatological changes that may have occurred since the 1991 model was published. There was no change, so the original value of .51 cm (0.0167 ft) of evaporation per month was used. The model recommendations hereafter are referred to as the *original recommendation*, R_o. R_o data are presented in figure 5.

Tree Number	R_o (m^3)
1	5.999
2	7.355
3	9.154
4	0.955
5	1.390
6	17.943
7	3.892
8	8.137
9	2.988
10	6.488
11	4.075
12	5.777

Figure 5- Original recommended volumes (R_o) calculated using the same parameters as in the 1991 model

CHAPTER III

RESULTS AND DISCUSSION

Comparison of Lindsey-Bassuk to Occupied Soil Volumes- The recommendations calculated using the parameters from the Lindsey Bassuk (LB) model, R_o, were compared to the occupied soil volume of each tree, V_o. V_o was subtracted from R_o, yielding the calculated difference between the occupied soil volume and the volume that would have been recommended for each tree using LB. The percent error was calculated by dividing the difference by V_o and multiplying by 100 (figure 6).

Tree Number	*Ro*	*Vo*	Difference (*Ro-Vo*)	% Error
1	5.999	8.18	-2.18	-26.64
2	7.355	13.42	-6.07	-45.20
3	9.154	27.23	-18.08	-66.39
4	0.955	1.28	-0.33	-25.64
5	1.390	2.67	-1.28	-47.96
6	17.943	21.03	-3.09	-14.68
7	3.892	12.29	-8.40	-68.32
8	8.137	19.61	-11.47	-58.50
9	2.988	6.54	-3.55	-54.28
10	6.488	16.90	-10.42	-61.62
11	4.075	9.13	-5.06	-55.38
12	5.777	9.56	-3.79	-39.59

Figure 6- Original recommended volumes (R_0) compared to the actual occupied volumes (V_o), all in cubic meters

For each of the twelve trees in the study, LB underestimated the rooting volume occupied by the trees. V_o was underestimated by a mean of 47% with a standard deviation of 17.25%. A paired t-test indicates that the difference between R_o and V_o is highly significant (Figure 7).

Mean Difference	-6.1406
Standard Error	1.48
p-value	0.0008*

Figure 7- Mean difference (R_o-V_o) and associated p-value

Modifications of the LB Model- Because LB resulted in significant underestimations of occupied soil volume, we decided to ways in which the parameters in the model could be modified. Our objective was to overcome deficiencies in the model that were resulting in such significant underestimations of V_o. Each parameter was investigated for its potential to be modified.

Leaf Area Index- In the 1991 LB model, a leaf area index of four is multiplied by the crown projection to produce an estimation of leaf area. Four was chosen based on empirical studies whereby leaves were removed from small trees. The total leaf area was measured, and then divided by the crown projection of the trees. Little leaf area index data has been published for urban trees. Further, because tree canopies tend to thin as they get larger, if anything we assume that an LAI of four may actually be an overestimation of the true LAI of the twelve trees in the study, which was not measured. Modifying LAI by arbitrarily adding additional layers to derive larger soil volumes would be an imprudent strategy, since doing so could not be supported by the literature. However, LB does not take into account water use by turf growing over the root systems of trees. Brede and Duich (1984) suggest that vigorous polyculture cool-season turf plots may obtain leaf area index values nearing 4. Their results also indicate that within their study, some monoculture plots had LAI values that were much lower, though specific data was not presented. Similarly, Brede and Duich (1984; 2) found that turf LAI varies based on height at time of mowing, with LAI values ranging from less than 1 to 2 in Kentucky bluegrass-perennial ryegrass mixtures.

Based on the range of LAI values for turf found in the literature, we attempted to estimate the water use by the turf growing over the root zone of each of our twelve trees. We estimated turf water use using the same method as was used in the LB calculations. LAI was multiplied by the area of the root system (the area substitution for crown projection, since the root systems are larger than the crown projection), by the 30 year average Pan evaporation for July (.51 cm/.0167 feet per day) and by a conversion factor. As will be discussed in a following section, we made the calculations using a correction factor of .2 and .3.

turf area x *LAI* x *highest mean daily pan evaporation* x *correction factor (ratio of leaf transpiration to pan evaporation) = daily turf water use*

The assumption being made here is that turf evapotranspiration is equivalent to tree evapotranspiration as a ratio of pan evaporation.

<u>Pan Evaporation Correction Factor-</u> The Lindsey Bassuk model uses a correction factor to account for the fact that leaf evapotranspiration is not equivalent to pan evaporation. Leaves transpire only a portion of evaporation from an open pan. The ratio of leaf water loss to pan evaporation is treated as a constant in LB. Their research on small trees indicated a ratio of .3. However, based on data indicating that the ratio decreases rapidly with increasing leaf area (due primarily to leaf shading), the LB model uses a ratio of .2. The choice to use a smaller ratio is a significant one, as the following example suggests.

Imagine a hypothetical tree with an LAI of 4 and a crown projection of 100 square feet. Using a correction factor of .2 and .51 cm (0.0167 ft) per day maximum pan evaporation, the estimation of whole-tree water use would be calculated as .038 cubic meters (1.34 cubic feet) of water (37.9 L/ 10 gallons) per day. If the larger ratio of .3 is used for the same tree, the estimation increases

to .4 cubic meters (2 cubic feet), or 56.78L (15 gallons) of water per day; not an insignificant difference. The soil volume required to support the increased water reservoir between precipitation events would increase likewise. Assuming an available water holding capacity of .2 and a precipitation interval of 10 days, the soil volume recommendation using the .2 ratio would be 1.89 cubic meters (67 cubic feet). Under the same conditions but using the .3 ratio, the recommended soil volume increases to 2.83 cubic meters (100 cubic feet). While this is a hypothetical example, the result is clear. Calculating soil volumes using a smaller ratio of leaf transpiration to pan evaporation results in significantly smaller recommendations. We did not conduct research to measure the ratio between leaf transpiration and pan evaporation. Because the research leading to the creation of the LB method empirically measured larger ratios than what ultimately was used as a constant in the published method, we decided to manipulate that part of the method using the larger ratio.

Regardless of which ratio was being used, the same ratio was applied to calculations of both turf water use and tree water use. We found no data in the literature to suggest a different ratio for turf compared to trees, so we assume that tree leaves and turf leaves experience equivalent transpiration.

<u>Precipitation Interval-</u> The LB method multiplies the amount of soil needed to support the tree's daily water use by a precipitation interval. The interval used in the original model is ten days, based on the determination that in Ithaca, NY, "92% of all dry periods (less than 1/10th" of rainfall) lasted 10 days or fewer. In other words, 92% of the time, Ithaca will receive at least 1/10th inch of rain every ten days. The assumption are "1) that sufficient soil water storage occurs from November to April so that the soil is fully recharged in May and 2) the calculated soul volume will hold sufficient water to carry a tree through the interval chosen, after which recharge

of soil water would occur through precipitation, the water table, lateral water movement, or perhaps irrigation". We determined that determining the precipitation interval based on 1/10th inch of rain required re-examination. The 1991 paper also acknowledges that soil water availability would be best estimated using information about soil textural classifications and soil profile descriptions. Since that information is mostly unavailable for heterogeneous urban soils, precipitation rates are the most effective way to estimate water availability for tree uptake. While a search of the literature reveals no scientific investigations into recharge of urban soils, a basic thought experiment reveals that for a soil with an available water capacity of 20%, 1/10th of an inch would only provide moisture for the top ½ inch, assuming a soil starting at the permanent wilting point, a bare soil surface with adequate capacity for infiltration, and a pressure head great enough to carry the water vertically into the soil profile. Clearly, soils rarely reach the permanent wilting point during moist northeastern growing seasons, but the argument stands for illustrative purposes. 1/10th of an inch of precipitation is unlikely to be effective, especially when taking into account canopy interception, evaporation from leaf surfaces and runoff. A ten day interval of such small rain events may lead to soil volume recommendations that are smaller than they should be. We made the decision to recalculate soil volume recommendations using an extended precipitation interval. In Ithaca, NY during the years 1982 to 2012, a rainfall event of at least ½" occurs on average every 16 days from May through August. Again, there is little information regarding urban soil recharge, so ½" was chosen arbitrarily.

Calculating soil volume recommendations using a larger precipitation interval yields larger soil volumes, but we acknowledge that this method is still a crude one. We calculated the average number of days between ½ inch precipitation events, and ignored any smaller rainfall events occurring between ½ inch events. Clearly, soil water recharge would be greater if the ½ inch

event was preceded by several events of, say, ¼ inch. Thus the assumption of drought between events of at least ½ inch likely inflates soil volume requirements since it assumes no other events or processes by which moisture enters the soil profile.

Available Water Holding Capacity- The LB method requires that the estimation of daily water use be divided by soil available water capacity to yield a soil volume able to support the tree's water needs for one day. For sake of example, they published a calculation using a silt loam with an AWHC of 19%. Standard practice has been to use 19% AWHC as a constant, rather than specifying a site-specific AWHC. As noted above in the discussion on precipitation intervals, LB acknowledges that soil water availability would be best estimated using information about soil textural classifications and soil profile descriptions. While that information is largely unavailable for urban environments, the information as to site-specific AWHC is readily available through a submission of a soil sample to any soil analysis laboratory. The soil in which the twelve trees in our study were growing had a very high mean AWHC of 32% and the textural class was clay loam. Mathematically, dividing the estimated daily whole-tree water use by 32% would result in smaller recommendations than would dividing by 19%. Since the original model resulted in significantly underestimated soil volume recommendations, it would seem like an unproductive strategy to use the measured AWHC values for our trees, given our goal of reducing the error between the calculated recommendation and the occupied soil volume. Regardless, we decided to compute recommendations using site-specific data for several reasons. First, our trees are most definitely more affected by site-specific conditions than they are by any arbitrary mathematical standard. Second, even though using site-specific AWHC data would decrease recommendations, the combination of this strategy with the above-described method of

accounting for turf water use might make up for the difference, since accounting for turf water use dramatically increases the water use and associated soil volume calculations of the combined tree-turf system.

List of Methods- Based on the various parameter variations that we determined to be viable candidates for alteration, we listed potential combinations of the parameters that would serve as new methods for calculating soil volume recommendations. There are twenty four methods. The levels of each parameter that we investigated are shown in figure 8. The list of the parameter levels for twenty four new methods is in figure 9.

Parameter	Levels
Tree LAI	4
Turf LAI	2, 3, 4
Pan Evaporation Correction Factor	.2, .3
Precipitation Interval	10 days, 16 days
Available Water-holding Capacity	19%, Measured AWHC per tree

Figure 8- Levels of each parameter that was modified

Method	Tree LAI	Turf LAI	Pan	Ratio	Precip	AWHC
0	4	X	0.0167	0.2	10	19.9
1	4	2	0.0167	0.2	10	19.9
2	4	3	0.0167	0.2	10	19.9
3	4	4	0.0167	0.2	10	19.9
4	4	2	0.0167	0.2	16	19.9
5	4	3	0.0167	0.2	16	19.9
6	4	4	0.0167	0.2	16	19.9
7	4	2	0.0167	0.3	10	19.9
8	4	3	0.0167	0.3	10	19.9
9	4	4	0.0167	0.3	10	19.9
10	4	2	0.0167	0.3	16	19.9
11	4	3	0.0167	0.3	16	19.9
12	4	4	0.0167	0.3	16	19.9
13	4	2	0.0167	0.2	10	Measured
14	4	3	0.0167	0.2	10	Measured
15	4	4	0.0167	0.2	10	Measured
16	4	2	0.0167	0.2	16	Measured
17	4	3	0.0167	0.2	16	Measured
18	4	4	0.0167	0.2	16	Measured
19	4	2	0.0167	0.3	10	Measured
20	4	3	0.0167	0.3	10	Measured
21	4	4	0.0167	0.3	10	Measured
22	4	2	0.0167	0.3	16	Measured
23	4	3	0.0167	0.3	16	Measured
24	4	4	0.0167	0.3	16	Measured

Figure 9- List of twenty four parameter levels for each of twenty four new iterations of LB. Method 0 contains the same parameter levels as the original LB method. Method 0 did not account for turf water use.

The combinations of parameter levels making up each of the twenty four methods were used to calculate twenty four new soil volume recommendations for each tree. Figures 10 through 21 show the occupied soil volume (V_o), the recommended soil volume (R_x) for each of the new methods, the difference between V_o and R_x, and the percent error between V_o and R_x. A negative difference and percent error indicates an underestimation of R_x.

Tree Number	Method	Vo	Rx	Difference	% error
1	0	8.18	6.00	-2.18	-26.64
1	1	8.18	12.03	3.85	47.14
1	2	8.18	14.91	6.73	82.29
1	3	8.18	17.78	9.60	117.45
1	4	8.18	19.25	11.07	135.42
1	5	8.18	23.85	15.67	191.67
1	6	8.18	28.45	20.27	247.92
1	7	8.18	18.05	9.87	120.71
1	8	8.18	22.36	14.18	173.44
1	9	8.18	26.67	18.50	226.17
1	10	8.18	28.88	20.70	253.14
1	11	8.18	35.78	27.60	337.51
1	12	8.18	42.68	34.50	421.88
1	13	8.18	7.68	-0.49	-6.05
1	14	8.18	9.52	1.34	16.40
1	15	8.18	11.35	3.18	38.85
1	16	8.18	12.29	4.12	50.33
1	17	8.18	15.23	7.05	86.24
1	18	8.18	18.17	9.99	122.16
1	19	8.18	11.52	3.35	40.93
1	20	8.18	14.28	6.10	74.60
1	21	8.18	17.03	8.85	108.28
1	22	8.18	18.44	10.26	125.49
1	23	8.18	22.85	14.67	179.37
1	24	8.18	27.25	19.07	233.24

Figure 10- Occupied soil volume (V_o), Calculated soil volume for each of the twenty four new methods (R_x) and the associated difference and % error between V_o and R_x for tree 1

Tree Number	Method	Vo	Rx	Difference	% error
2	0	13.42	7.35	-6.07	-45.20
2	1	13.42	17.14	3.72	27.70
2	2	13.42	21.86	8.44	62.86
2	3	13.42	26.58	13.15	98.01
2	4	13.42	27.42	14.00	104.32
2	5	13.42	34.97	21.55	160.57
2	6	13.42	42.52	29.10	216.82
2	7	13.42	25.71	12.29	91.55
2	8	13.42	32.79	19.36	144.28
2	9	13.42	39.86	26.44	197.01
2	10	13.42	41.13	27.71	206.48
2	11	13.42	52.46	39.04	290.85
2	12	13.42	63.78	50.36	375.22
2	13	13.42	10.29	-3.13	-23.33
2	14	13.42	13.12	-0.30	-2.22
2	15	13.42	15.96	2.53	18.88
2	16	13.42	16.46	3.04	22.67
2	17	13.42	21.00	7.58	56.44
2	18	13.42	25.53	12.11	90.21
2	19	13.42	15.44	2.01	15.01
2	20	13.42	19.68	6.26	46.67
2	21	13.42	23.93	10.51	78.33
2	22	13.42	24.70	11.28	84.01
2	23	13.42	31.50	18.07	134.67
2	24	13.42	38.29	24.87	185.32

Figure 11- Occupied soil volume (V_o), Calculated soil volume for each of the twenty four new methods (R_x) and the associated difference and % error between V_o and R_x for tree 2

Tree Number	Method	Vo	Rx	Difference	% error
3	0	27.23	9.15	-18.08	-66.39
3	1	27.23	28.30	1.07	3.92
3	2	27.23	37.87	10.64	39.07
3	3	27.23	47.45	20.21	74.23
3	4	27.23	45.28	18.05	66.27
3	5	27.23	60.60	33.37	122.52
3	6	27.23	75.92	48.68	178.77
3	7	27.23	42.45	15.22	55.88
3	8	27.23	56.81	29.58	108.61
3	9	27.23	71.17	43.94	161.34
3	10	27.23	67.92	40.69	149.41
3	11	27.23	90.90	63.66	233.78
3	12	27.23	113.87	86.64	318.15
3	13	27.23	16.35	-10.88	-39.95
3	14	27.23	21.89	-5.35	-19.63
3	15	27.23	27.42	0.19	0.69
3	16	27.23	26.17	-1.07	-3.91
3	17	27.23	35.02	7.79	28.59
3	18	27.23	43.87	16.64	61.10
3	19	27.23	24.53	-2.70	-9.92
3	20	27.23	32.83	5.60	20.55
3	21	27.23	41.13	13.90	51.03
3	22	27.23	39.25	12.02	44.13
3	23	27.23	52.53	25.30	92.89
3	24	27.23	65.81	38.57	141.64

Figure 12- Occupied soil volume (V_o), Calculated soil volume for each of the twenty four new methods (R_x) and the associated difference and % error between V_o and R_x for tree 3

Tree Number	Method	Vo	Rx	Difference	% error
4	0	1.28	0.96	-0.33	-25.64
4	1	1.28	1.90	0.62	48.19
4	2	1.28	2.35	1.07	83.34
4	3	1.28	2.81	1.52	118.50
4	4	1.28	3.05	1.76	137.10
4	5	1.28	3.77	2.48	193.35
4	6	1.28	4.49	3.21	249.59
4	7	1.28	2.85	1.57	122.28
4	8	1.28	3.53	2.25	175.01
4	9	1.28	4.21	2.93	227.74
4	10	1.28	4.57	3.28	255.65
4	11	1.28	5.65	4.37	340.02
4	12	1.28	6.74	5.45	424.39
4	13	1.28	1.24	-0.04	-3.43
4	14	1.28	1.53	0.25	19.48
4	15	1.28	1.83	0.54	42.38
4	16	1.28	1.98	0.70	54.51
4	17	1.28	2.46	1.17	91.16
4	18	1.28	2.93	1.64	127.81
4	19	1.28	1.86	0.58	44.85
4	20	1.28	2.30	1.02	79.21
4	21	1.28	2.74	1.46	113.58
4	22	1.28	2.98	1.69	131.76
4	23	1.28	3.68	2.40	186.74
4	24	1.28	4.39	3.10	241.72

Figure 13- Occupied soil volume (V_o), Calculated soil volume for each of the twenty four new methods (R_x) and the associated difference and % error between V_o and R_x for tree 4

Tree Number	Method	Vo	Rx	Difference	% error
5	0	2.67	1.39	-1.28	-47.96
5	1	2.67	3.33	0.66	24.81
5	2	2.67	4.27	1.60	59.97
5	3	2.67	5.21	2.54	95.12
5	4	2.67	5.33	2.66	99.70
5	5	2.67	6.83	4.16	155.95
5	6	2.67	8.34	5.67	212.20
5	7	2.67	5.00	2.33	87.22
5	8	2.67	6.41	3.74	139.95
5	9	2.67	7.82	5.15	192.69
5	10	2.67	8.00	5.33	199.55
5	11	2.67	10.25	7.58	283.93
5	12	2.67	12.50	9.83	368.30
5	13	2.67	1.95	-0.72	-26.89
5	14	2.67	2.50	-0.17	-6.30
5	15	2.67	3.05	0.38	14.30
5	16	2.67	3.12	0.45	16.98
5	17	2.67	4.00	1.33	49.93
5	18	2.67	4.88	2.21	82.87
5	19	2.67	2.93	0.26	9.67
5	20	2.67	3.75	1.08	40.56
5	21	2.67	4.58	1.91	71.44
5	22	2.67	4.69	2.02	75.47
5	23	2.67	6.01	3.33	124.89
5	24	2.67	7.32	4.65	174.31

Figure 14- Occupied soil volume (V_o), Calculated soil volume for each of the twenty four new methods (R_x) and the associated difference and % error between V_o and R_x for tree 5

Tree Number	Method	Vo	Rx	Difference	% error
6	0	21.03	17.94	-3.09	-14.68
6	1	21.03	33.58	12.55	59.66
6	2	21.03	40.97	19.94	94.82
6	3	21.03	48.37	27.33	129.97
6	4	21.03	53.73	32.69	155.46
6	5	21.03	65.56	44.52	211.70
6	6	21.03	77.38	56.35	267.95
6	7	21.03	50.37	29.34	139.49
6	8	21.03	61.46	40.43	192.22
6	9	21.03	72.55	51.52	244.96
6	10	21.03	80.59	59.56	283.19
6	11	21.03	98.33	77.30	367.56
6	12	21.03	116.08	95.05	451.93
6	13	21.03	19.51	-1.53	-7.25
6	14	21.03	23.80	2.77	13.17
6	15	21.03	28.10	7.06	33.59
6	16	21.03	31.21	10.18	48.39
6	17	21.03	38.08	17.05	81.07
6	18	21.03	44.95	23.92	113.74
6	19	21.03	29.26	8.23	39.12
6	20	21.03	35.70	14.67	69.75
6	21	21.03	42.14	21.11	100.38
6	22	21.03	46.81	25.78	122.59
6	23	21.03	57.12	36.09	171.60
6	24	21.03	67.43	46.40	220.61

Figure 15- Occupied soil volume (V_o), Calculated soil volume for each of the twenty four new methods (R_x) and the associated difference and % error between V_o and R_x for tree 6

Tree Number	Method	Vo	Rx	Difference	% error
7	0	12.29	3.89	-8.40	-68.32
7	1	12.29	12.72	0.43	3.48
7	2	12.29	17.04	4.75	38.64
7	3	12.29	21.36	9.07	73.79
7	4	12.29	20.35	8.06	65.57
7	5	12.29	27.26	14.97	121.82
7	6	12.29	34.17	21.88	178.07
7	7	12.29	19.07	6.79	55.23
7	8	12.29	25.55	13.27	107.96
7	9	12.29	32.03	19.75	160.69
7	10	12.29	30.52	18.23	148.36
7	11	12.29	40.89	28.60	232.73
7	12	12.29	51.25	38.96	317.11
7	13	12.29	7.27	-5.01	-40.80
7	14	12.29	9.74	-2.54	-20.69
7	15	12.29	12.22	-0.07	-0.58
7	16	12.29	11.64	-0.65	-5.29
7	17	12.29	15.59	3.30	26.89
7	18	12.29	19.55	7.26	59.07
7	19	12.29	10.91	-1.38	-11.20
7	20	12.29	14.62	2.33	18.96
7	21	12.29	18.32	6.04	49.12
7	22	12.29	17.46	5.17	42.07
7	23	12.29	23.39	11.10	90.34
7	24	12.29	29.32	17.03	138.60

Figure 16- Occupied soil volume (V_o), Calculated soil volume for each of the twenty four new methods (R_x) and the associated difference and % error between V_o and R_x for tree 7

Tree Number	Method	Vo	Rx	Difference	% error
8	0	19.61	8.14	-11.47	-58.50
8	1	19.61	22.31	2.70	13.77
8	2	19.61	29.20	9.59	48.93
8	3	19.61	36.09	16.48	84.08
8	4	19.61	35.69	16.08	82.04
8	5	19.61	46.72	27.11	138.28
8	6	19.61	57.75	38.14	194.53
8	7	19.61	33.46	13.85	70.66
8	8	19.61	43.80	24.19	123.39
8	9	19.61	54.14	34.53	176.12
8	10	19.61	53.53	33.93	173.05
8	11	19.61	70.08	50.47	257.43
8	12	19.61	86.62	67.01	341.80
8	13	19.61	13.10	-6.51	-33.20
8	14	19.61	17.14	-2.46	-12.56
8	15	19.61	21.19	1.58	8.08
8	16	19.61	20.96	1.35	6.88
8	17	19.61	27.43	7.82	39.91
8	18	19.61	33.91	14.30	72.93
8	19	19.61	19.65	0.04	0.20
8	20	19.61	25.72	6.11	31.16
8	21	19.61	31.79	12.18	62.13
8	22	19.61	31.43	11.83	60.32
8	23	19.61	41.15	21.54	109.86
8	24	19.61	50.86	31.25	159.40

Figure 17- Occupied soil volume (V_o), Calculated soil volume for each of the twenty four new methods (R_x) and the associated difference and % error between V_o and R_x for tree 8

Tree Number	Method	Vo	Rx	Difference	% error
9	0	6.54	2.99	-3.55	-54.28
9	1	6.54	7.72	1.19	18.19
9	2	6.54	10.02	3.49	53.34
9	3	6.54	12.32	5.78	88.50
9	4	6.54	12.36	5.82	89.10
9	5	6.54	16.04	9.50	145.35
9	6	6.54	19.71	13.18	201.60
9	7	6.54	11.59	5.05	77.28
9	8	6.54	15.03	8.50	130.01
9	9	6.54	18.48	11.94	182.75
9	10	6.54	18.54	12.00	183.65
9	11	6.54	24.05	17.52	268.02
9	12	6.54	29.57	23.03	352.39
9	13	6.54	4.09	-2.45	-37.48
9	14	6.54	5.30	-1.23	-18.89
9	15	6.54	6.52	-0.02	-0.29
9	16	6.54	6.54	0.00	0.03
9	17	6.54	8.48	1.95	29.78
9	18	6.54	10.43	3.89	59.53
9	19	6.54	6.13	-0.41	-6.22
9	20	6.54	7.95	1.42	21.67
9	21	6.54	9.78	3.24	49.56
9	22	6.54	9.81	3.27	50.04
9	23	6.54	12.72	6.19	94.67
9	24	6.54	15.64	9.10	139.30

Figure 18- Occupied soil volume (V_o), Calculated soil volume for each of the twenty four new methods (R_x) and the associated difference and % error between V_o and R_x for tree 9

Tree Number	Method	Vo	Rx	Difference	% error
10	0	16.90	6.49	-10.42	-61.62
10	1	16.90	18.68	1.78	10.50
10	2	16.90	24.62	7.72	45.66
10	3	16.90	30.57	13.66	80.81
10	4	16.90	29.89	12.98	76.80
10	5	16.90	39.40	22.49	133.05
10	6	16.90	48.91	32.00	189.30
10	7	16.90	28.02	11.12	65.75
10	8	16.90	36.93	20.03	118.48
10	9	16.90	45.85	28.94	171.22
10	10	16.90	44.83	27.93	165.20
10	11	16.90	59.10	42.19	249.57
10	12	16.90	73.36	56.45	333.94
10	13	16.90	10.23	-6.68	-39.49
10	14	16.90	13.48	-3.42	-20.24
10	15	16.90	16.74	-0.17	-0.99
10	16	16.90	16.37	-0.54	-3.19
10	17	16.90	21.57	4.67	27.61
10	18	16.90	26.78	9.88	58.42
10	19	16.90	15.34	-1.56	-9.24
10	20	16.90	20.22	3.32	19.64
10	21	16.90	25.11	8.20	48.51
10	22	16.90	24.55	7.64	45.22
10	23	16.90	32.36	15.45	91.42
10	24	16.90	40.17	23.27	137.62

Figure 19- Occupied soil volume (V_o), Calculated soil volume for each of the twenty four new methods (R_x) and the associated difference and % error between V_o and R_x for tree 10

Tree Number	Method	Vo	Rx	Difference	% error
11	0	9.13	4.08	-5.06	-55.38
11	1	9.13	10.69	1.56	17.04
11	2	9.13	13.90	4.77	52.19
11	3	9.13	17.11	7.98	87.35
11	4	9.13	17.10	7.97	87.26
11	5	9.13	22.24	13.11	143.51
11	6	9.13	27.38	18.24	199.75
11	7	9.13	16.03	6.90	75.56
11	8	9.13	20.85	11.72	128.29
11	9	9.13	25.67	16.53	181.02
11	10	9.13	25.66	16.52	180.89
11	11	9.13	33.36	24.23	265.26
11	12	9.13	41.07	31.93	349.63
11	13	9.13	6.46	-2.68	-29.30
11	14	9.13	8.40	-0.74	-8.07
11	15	9.13	10.34	1.20	13.17
11	16	9.13	10.33	1.20	13.11
11	17	9.13	13.43	4.30	47.09
11	18	9.13	16.54	7.40	81.07
11	19	9.13	9.69	0.55	6.05
11	20	9.13	12.60	3.46	37.90
11	21	9.13	15.50	6.37	69.75
11	22	9.13	15.50	6.36	69.67
11	23	9.13	20.15	11.02	120.64
11	24	9.13	24.81	15.67	171.60

Figure 20- Occupied soil volume (V_o), Calculated soil volume for each of the twenty four new methods (R_x) and the associated difference and % error between V_o and R_x for tree 11

Tree Number	Method	Vo	Rx	Difference	% error
12	0	9.56	5.78	-3.79	-39.59
12	1	9.56	12.77	3.21	33.57
12	2	9.56	16.14	6.57	68.73
12	3	9.56	19.50	9.93	103.88
12	4	9.56	20.44	10.88	113.72
12	5	9.56	25.82	16.25	169.96
12	6	9.56	31.20	21.63	226.21
12	7	9.56	19.16	9.60	100.36
12	8	9.56	24.20	14.64	153.09
12	9	9.56	29.25	19.68	205.82
12	10	9.56	30.66	21.09	220.57
12	11	9.56	38.73	29.16	304.95
12	12	9.56	46.79	37.23	389.32
12	13	9.56	8.19	-1.38	-14.41
12	14	9.56	10.34	0.78	8.12
12	15	9.56	12.49	2.93	30.64
12	16	9.56	13.10	3.53	36.94
12	17	9.56	16.54	6.98	72.99
12	18	9.56	19.99	10.43	109.03
12	19	9.56	12.28	2.71	28.39
12	20	9.56	15.51	5.95	62.17
12	21	9.56	18.74	9.18	95.96
12	22	9.56	19.64	10.08	105.42
12	23	9.56	24.81	15.25	159.48
12	24	9.56	29.99	20.42	213.54

Figure 21- Occupied soil volume (V_o), Calculated soil volume for each of the twenty four new methods (R_x) and the associated difference and % error between V_o and R_x for tree 12

Figure 22 shows the mean absolute error for each of the twenty four new methods in addition to the original method, 0. For all analysis from here forward, absolute error was used. We were less concerned about whether the error was negative or positive. Our objective was to minimize the error in both directions, and absolute error provided a more useful and informative measure of comparison.

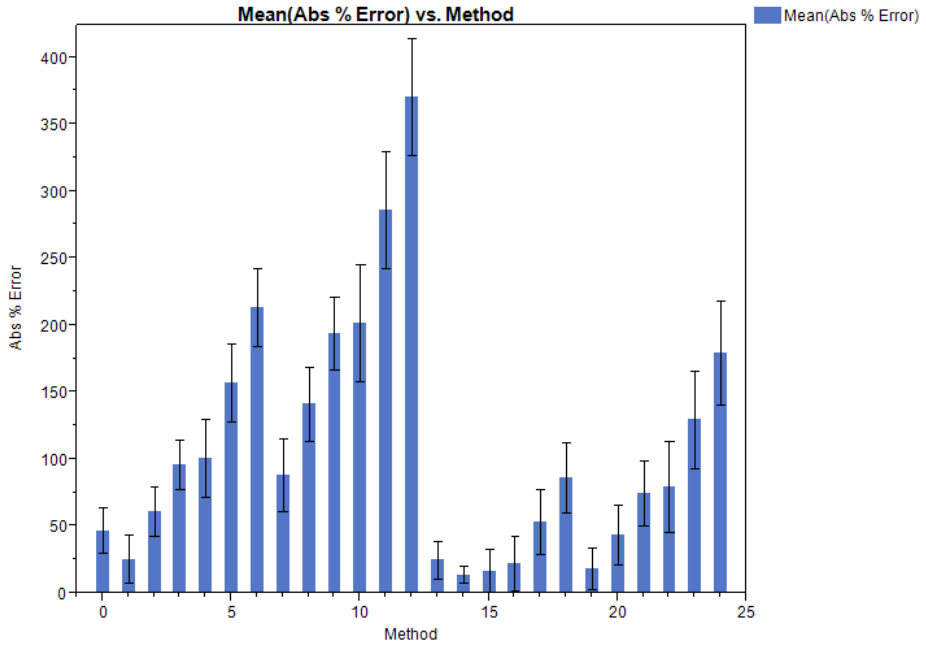


Figure 22- Mean absolute % error for each of the twenty four methods, plus LB (method 0). Error bars were constructed using 1 standard deviation from the mean.

As is evident in figure 22, many of the twenty four new methods yielded absolute errors that were much larger than method 0, the original LB method. Those methods were automatically rejected for further analysis. Again, our objective was to reduce the error between the recommended soil volume and the occupied soil volume. Mean absolute errors that were larger than R_o did not meet that objective.

For each tree, the method which provided the smallest absolute error was recorded (figure 23).

Tree Number	Method Number	Vo	Rx	Abs % Error
1	13	8.18	7.68	6.05
2	14	13.42	13.12	2.22
3	15	27.23	27.42	0.69
4	13	1.28	1.24	3.43
5	14	2.67	2.50	6.30
6	13	21.03	19.51	7.25
7	15	12.29	12.22	0.58
8	19	19.61	19.65	0.20
9	16	6.54	6.54	0.03
10	15	16.90	16.74	0.99
11	19	9.13	9.69	6.05
12	14	9.56	10.34	8.12

Figure 23- Methods resulting in the smallest error for each tree and the associated occupied volume, recommendation resulting from that method, and the absolute percent error.

Methods 13, 14, 15, 16 and 19 were the only methods that provided the most reduced error for at least one of the twelve trees in the study. Because none of the other methods were ever the 'best' for any individual tree, all other methods were excluded from all further analysis, regardless of whether their mean absolute error was smaller than method 0. The parameters used to construct method 13, 14, 15, 16 and 19 are shown in figure 24.

Method	Tree LAI	Turf LAI	Pan	Ratio	Precip	AWHC
13	4	2	0.0167	0.2	10	Measured
14	4	3	0.0167	0.2	10	Measured
15	4	4	0.0167	0.2	10	Measured
16	4	2	0.0167	0.2	16	Measured
19	4	2	0.0167	0.3	10	Measured

Figure 24- Parameters used to construct the methods which provided the smallest absolute percent error for at least one tree

Three of the five 'best methods' were calculated using a turf LAI of 2. That value is reasonable, considering the range of turf LAI's found in the literature, and based on the fact that the turf growing over the root systems of the studied trees is comprised of mixed cool-season grasses.

Extremely robust turf may well have LAI values higher than 2. LAI was not measured on the turf in our study, but it is notable that accounting for turf water use using the same method as we did for tree water use seems to have proven a reasonable strategy, given the results. Also of note it that in four of the five 'best methods', the original ratio of leaf transpiration to pan evaporation was used (.2). This result indicates that the assertion made in LB is likely correct; as canopy size increases, the ratio of leaf transpiration to pan evaporation decreases. Surprisingly, all but one of the 'best methods' were calculated using the measured AWHC for each tree. As was discussed earlier, our study site has soil with very high AWHC, and using such high values would result in lower soil volume recommendations than would the standard value of 19%. Accounting for turf water use likely over-estimated soil volume, and using the measured AWHC values may have acted to balance that over-estimation to yield reasonably accurate recommendations. The ten day precipitation interval was also used in computations for four of the five methods. The same is likely the case with precipitation as with AWHC. Using the smaller interval may act as a buffer against overestimations of turf water use.

For each of the twelve trees in the study, the absolute percent error associated with the recommended soil volumes that were calculated for each of the above methods was recorded (figure 25).

	Method					
Tree Number	0	13	14	15	16	19
1	26.64	6.05	16.40	38.85	50.33	40.93
2	45.20	23.33	2.22	18.88	22.67	15.01
3	66.39	39.95	19.63	0.69	3.91	9.92
4	25.64	3.43	19.48	42.38	54.51	44.85
5	47.96	26.89	6.30	14.30	16.98	9.67
6	14.68	7.25	13.17	33.59	48.39	39.12
7	68.32	40.80	20.69	0.58	5.29	11.20
8	58.50	33.20	12.56	8.08	6.88	0.20
9	54.28	37.48	18.89	0.29	0.03	6.22
10	61.62	39.49	20.24	0.99	3.19	9.24
11	55.38	29.30	8.07	13.17	13.11	6.05
12	39.59	14.41	8.12	30.64	36.94	28.39
Mean	47.02	25.13	13.81	16.87	21.85	18.40
Std. Dev.	17.25	14.08	6.36	15.84	20.35	15.56

Figure 25- The absolute % error associated with each tree for each of the 'best methods'

All five 'best methods' resulted in improvements over method 0, the original LB method. However, despite the improvements, some of the mean absolute errors were still quite large. Paired t-tests were conducted to compare the absolute error associated with each method to the absolute error associated with method 0 (figure 26).

Method Comparison	p-value	Bonferroni Adj p-value	Mean Difference	Std Error
13 to 0	0.0001*	0.0005*	-21.885	1.58
14 to 0	0.0001*	0.0005*	-33.204	4.96778
15 to 0	0.0041*	0.0205*	-30.146	9.37722
16 to 0	0.0191*	0.0955	-25.164	10.6926
19 to 0	0.005*	0.025*	-28.618	9.20454

Figure 26- Results of paired t-tests comparing each 'best method' to the original LB method, method 0.

Before correcting for multiples comparisons, all of the selected method provided significant improvements over the LB method at α=.05. P-values were adjusted for multiple comparisons using the Bonferroni adjustment whereby the p-values were multiplied by the number of comparisons made (in this case, five). Once corrected, method 16 failed to provide significant

improvements over LB. The mean difference is the difference between the mean absolute percent error associated with method zero minus the mean absolute percent error associated with the method in the given comparison. Our goal was to find method with large negative mean differences, as that indicates a large improvement in percent error over LB. However, we had to balance a large negative mean difference with a large standard error. Method 14 provided both a large negative mean difference *and* a small standard error, indicating that method reliably and consistently provided major improvements over LB for each of the 12 trees in our study. Based on that fact, we conclude that method 14 is the best of the five methods that were chosen for analysis after the initial twenty four methods were reduced.

Regression Estimates- We were interested in determining if a relationship could be established between the various tree size metrics that we measured and the occupied soil volume, V_o. Were that the case, there would be merit in further researching this type of relationship as it could provide a simple alternative method to obtain soil volume recommendations given predictions of mature canopy size or trunk diameter. Crown volume and DBH have a strong linear relationship to one another (figure 27). As such, they were not included in a multivariate regression to predict V_o.

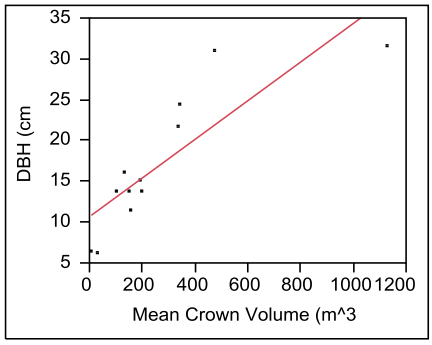
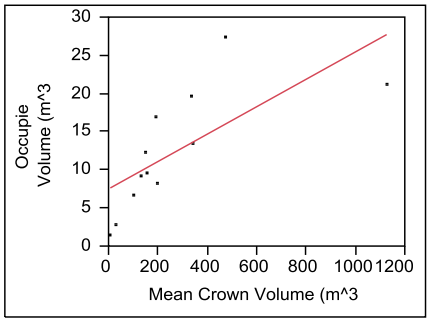


Figure 27- Regression report: Mean Crown Volume by DBH (R^2=.72)

Mean crown volume exhibits a weak but significant positive linear relationship with Occupied Volume (figure 28). However, because of the small sample size of this study and because of potential outliers exerting leverage, no conclusions may be drawn about the ability of crown volume to reliably predict occupied soil volume for any of the trees in this study, and especially for predictions about all trees in general. In fact the average absolute residual (difference between the observed and predicted occupied soil volume) is 4.25 cubic meters following this method.



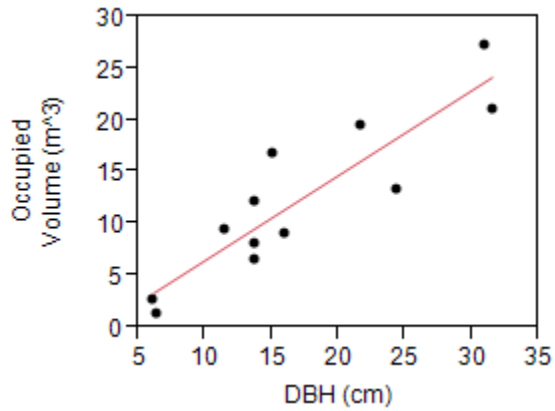
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	7.4831938	2.285905	3.27	0.0084*
Mean Crown Volume (m^3)	0.0179554	0.005792	3.10	0.0112*

Figure 28- Regression Report: Occupied Volume (m^3) by Mean Crown Volume (m^3) (R^2=.49)

Diameter at Breast Height (DBH) is a highly significant predictor of occupied soil volume for the twelve trees in this study, exhibiting a strong linear relationship (figure 29). The average absolute residual following this method is 2.97 cubic meters. Again, because of the small sample size in this study, generalizable recommendations for using DBH to predict occupied soil volume is problematic. Further, regression results using only twelve trees cannot adequately address

normality assumptions; the results are presented here to represent the point that additional research is needed to further establish the relationship between tree size metrics and occupied soil volume.



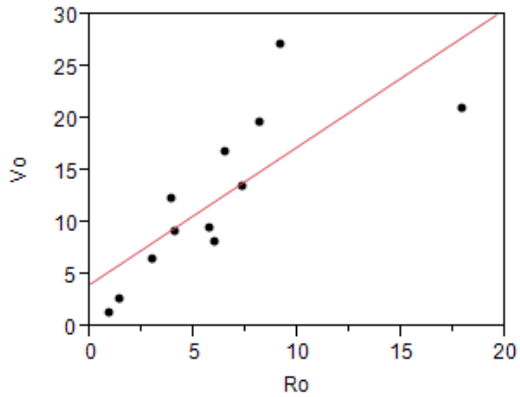
R^2=.8

Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	-1.652047	2.441438	-0.68	0.5140
DBH (cm)	0.8199157	0.129476	6.33	<.0001*

Figure 29- Regression Report: Occupied Volume (m^3) by DBH (cm) (R^2=.8)

Another interesting area of investigation was the relationship between the original LB recommendations, R_o, and the occupied soil volume V_o. As has been established elsewhere, LB dramatically underestimated V_o for the twelve tree in this study. A linear regression of actual occupied soil volume by the LB recommendations is shown in figure 30.



R^2=.59

Parameter Estimates

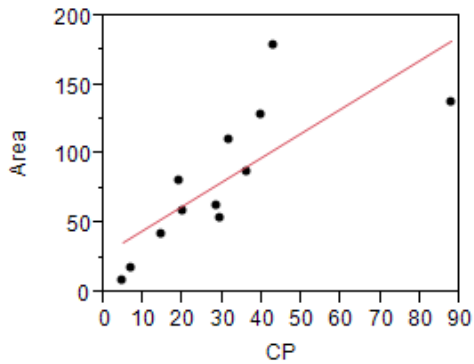
Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4.1449442	2.607262	1.59	0.1430
Ro	1.3229494	0.346091	3.82	0.0034*

Figure 30- Regression Report: Occupied Soil Volume (Vo) by LB Recommended soil volume (Ro).

While there is a significant linear relationship between the occupied soil volume and the original LB recommendations, the relationship is not strong enough to warrant drawing a broad conclusion about the ability of the original method to predict the occupied soil volume. Using R_o as part of a predictive equation would result in large errors, based on the data for these twelve trees, though the possibility is intriguing and warrants future research. However, better results may be obtained using the 'best; method' strategy that was the focus of this research.

Finally, we were interested in determining if we could establish a relationship between the rooting area and tree size metrics. The method that emerged as reducing the error between the occupied soil volume and the calculated recommended soil volume estimated turf water use based on the area of turf growing over the tree root systems. The ability to estimate rooting area, and thus turf area based on tree size metrics would be valuable. Most helpful would be to establish a relationship between crown projection and rooting area, since crown projection

already has to be used in the model to estimate whole-tree water use. The linear relationship between crown projection and rooting area is shown in figure 31.



R^2=.57

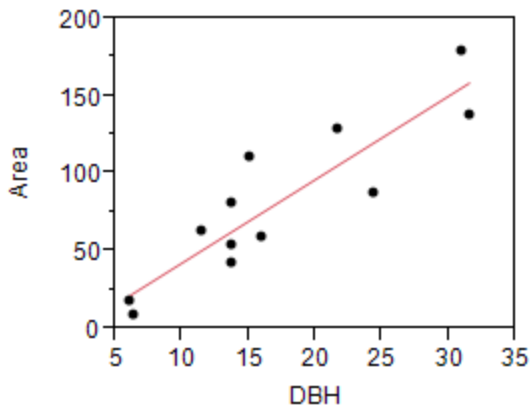
Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	28.087769	17.50091	1.60	0.1396
CP	1.7572342	0.477739	3.68	0.0043*

Figure 31- Regression Report: CP by Rooting Area

There is a significant linear relationship between CP and rooting area, but because there is significant lack of fit, the relationship is not strong enough to yield a simple ratio of CP to area. Again, further research into the relationship would be very valuable.

The relationship between DBH and rooting area shows a stronger relationship (figure 32).



R^2= .8

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-10.83999	16.02916	-0.68	0.5142
DBH	5.3825408	0.850068	6.33	<.0001*

Figure 32- Regression Report: DBH by Rooting Area

With an R^2 of .8 and a strongly significant positive linear relationship between DBH and rooting area, there is much promise in the potential of using DBH as a predictor of rooting area. However, this method would create the additional challenge of having to estimate a DBH for a tree several years after it is planted. More research is necessary before we would recommend estimating DBH and using it as a predictor of rooting area, though of the two tree metrics we measured, DBH is the most promising.

Comparison of Occupied Soil Volume to Common Root-Protection Recommendations- Several municipalities and tree care companies designate minimum tree root protection zones around existing trees during construction activity. Tree root protection zone recommendations range from protecting a radius of 1 to 1.5 feet for each inch of DBH. We compared the mean root extent of the experimental trees in our study to the root protection radii that would be protected according to the 1 and 1.5 foot protection methods (figure 33). Standard units were used to make this comparison, because that is the typical practice in professional forestry. For the twelve trees in our study, protecting 1 foot for every inch of DBH would only result in the protection of 42%

of root extent. Using the more liberal recommendation of 1.5 feet per inch of DBH, the mean root extent that would be protected rises to 63%. The maximum damage that may be caused to roots without resulting in severe reduction on tree function is unknown, though the ability to withstand damage is likely affected by tree age, condition and species. A safe approach is to protect as much of the root zone as possible. Our data would suggest that protecting at least a 1.5 foot radius for each inch of DBH is a good practice, though more research is needed to determine how trees variably respond to root disruption.

Tree Number	DBH	Mean Root Extent (ft)	1 Foot Protection Radius (ft)	% Protection 1 ft Radius	1.5 foot Protection Radius (ft)	% Protection 1.5 ft Radius
1	5.4	13.56	5.4	0.40	8.1	0.60
2	9.6	17.38	9.6	0.55	14.4	0.83
3	12	24.75	12.2	0.49	18.3	0.74
4	2.5	5.38	2.5	0.47	3.75	0.70
5	2.4	7.75	2.4	0.31	3.6	0.46
6	12	21.75	12.4	0.57	18.6	0.86
7	5.4	16.63	5.4	0.32	8.1	0.49
8	8.5	21.00	8.5	0.40	12.75	0.61
9	5.4	12.13	5.4	0.45	8.1	0.67
10	5.9	19.50	5.9	0.30	8.85	0.45
11	6.3	14.33	6.3	0.44	9.45	0.66
12	4.5	14.67	4.5	0.31	6.75	0.46
			Mean % Protection 1 ft Radius	**0.42**	**Mean % Protection 1.5 ft Radius**	**0.63**

Figure 33- Percent of root extent protected using two common root protection zone formulas

CHAPTER IV

CONCLUSIONS

We present results investigating the ability of the 1991 Lindsey/Bassuk soil volume recommendation for urban trees to predict the occupied soil volume of twelve existing *Acer rubrum*. We identified variations to the parameters in the original model that result in significantly improved predictions. While no one method stood out as being able to reduce the error between the calculated volume and the occupied volume for all trees to a level that consistently approximates the occupied volume, we did find that increasing the specificity of the parameters offers a tremendous advantage. Accounting for turf water use is perhaps our most important and valuable result. There is still a need to estimate root extent in order to determine amount of turf that should be included in turf water use estimations. Our results suggest that the square foot rooting area is approximately four to five times greater than DBH. We would suggest reducing competition for water from turf by mulching the root zone. On large trees where whole-tree mulching is impractical, we suggest accounting for turf water use over the entire area of the planting space opening or an area 4 to five times the estimated DBH of the mature tree. More research is necessary to strengthen the understanding of root extent and the relationship to tree size parameters. Such information would provide for much more precise estimations of the necessary area of turf to be accounted for.

Our research indicates that increasing the specificity regarding soil AWHC improves the ability to reduce the error between the calculated soil volume and the occupied soil volume. We recommend using site-specific soil data whenever it is available.

One difficult aspect of the LB model and its derivations discussed in this research is that it is predictive. The results are based on the ability to predict the mature size of a tree canopy, a

metric that is difficult to guess and is affected by a host of conditions that cannot be easily measured before the tree is actually in place and growing. There is a need for long-term and continuous measurements of urban tree growth across species and site conditions. Currently, practitioners have to make a best guess about potential tree size based on anecdotal evidence rather than data. There have been attempts to correlate mature tree size with designed planting space, and this type of research is valuable and should be expanded (Day & Amateis 2011, Sanders et. al. 2013).

Besides small sample size, another challenge we experienced in our research was lack of standardization of tree size. Our aim was to obtain a general picture of the ability of Lindsey/Bassuk to predict occupied soil volumes. However, that approach made it impossible to obtain normalized data, and it also didn't allow us to make observations about Lindsey/Bassuk's effectiveness based on tree size. Larger normalized samples are needed. However, open-grown trees that meet the criteria for a study like this are few and far between, and because the root investigation methods are invasive and potentially destructive, it is difficult to find trees that may be included in this type of study. We encourage the continued investigation into non-invasive root detection technologies in variable soil types. Such research, if found to be reliable, will make soil volume investigations much more approachable.

One of the major shortfalls of our methods is the assumption that tree roots exist in isolation from the surrounding soil. We considered the occupied soil volume to be that volume in which roots physically exist. We did not consider matric flow of water from surrounding soils as contributing any moisture to support tree growth. One would assume that additional sources of soil moisture would result in a further reduced need for trees to explore large soil volumes. If the Lindsey/Bassuk method did somehow predict recharge from matric flow, it would likely result in

smaller recommendations and thus larger errors when compared to occupied volumes. This presents further reason to support our finding that Lindsey/Bassuk underestimates true soil volume requirements.

Tree size metrics, especially DBH, shows real promise as an easy to measure predictor of occupied soil volume and thus soil volume requirements. Our results show a very strong linear relationship between DBH and soil volume. As research continues into planting pit size and soil volume requirements, we strongly advocate the collection of DBH and other size parameters so that correlations may be expanded and this type of method may be investigated further.

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