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REDESIGNING THE URBAN FOREST FROM THE GROUND BELOW: A NEW APPROACH TO SPECIFYING ADEQUATE SOIL VOLUMES FOR STREET TREES

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Summary

Current surveys have dramatically documented the plight of struggling and dying urban trees. Inadequate soil rooting volume is an important cause of this premature mortality. The soil acts as a vital reservoir, holding and then supplying water as the tree demands it. A weather-based methodology has been developed that enables the arboriculturist to size a tree pit or container based on a tree's daily expected water requirements, thereby reducing or eliminating water stress over a growing season. For use as a general estimate, a soil volume of 5 m^3 for a medium sized tree is recommended.

Introduction

Current studies indicate that tree cover in urban areas is significantly declining (MOLL, 1987; MOLL, 1989). Readily finding something to blame for this bleak phenomenon is easy, because while urban ecologies are dauntingly complex, they produce a brutal yet simple truth: trees will not endure where there is insufficient air, light, water or fertile soil.

Clearly, the most debilitating conflict is between the biological needs of trees whose roots systems generally lay near the surface and spread laterally, and the small confined areas they are relegated to in the design of urban streets. The roots of the tree are vital, yet it is the roots that are most frequently overlooked and disrupted in the urban environment. The typical street tree growing area or pit, which already is inhospitably sandwiched in a narrow strip between the road and sidewalk, competes for space with underground utilities, subways, and building foundations.

The small volumes of compacted soil that the roots have access to in these areas are either poorly drained, or more likely, cannot hold sufficient water to meet the tree's demand. Soil, overly wet or too dry, or even more

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simply, the lack of soil, accounts for most tree survival problems. Either way, vigorous root growth is impaired and severe constraints are placed upon healthy tree development. Inadequate underground rooting space then is one of the more important factors in the premature mortality of city trees (BERRANG *et al.*, 1985; KRIZEK and DUBIK, 1987; CLARK and KJELGREN, 1989; URBAN, 1989).

Problems in determining minimally adequate soil volumes

Current recommendations detailing appropriate soil volumes for trees have been culled from a variety of sources in the literature (Figure 1). Our recommendation is included for comparison. Many of these estimates are quite high, and in fact a few of these volumes would be impossible to achieve given the reality of the street environment. Some of these estimates are either simple rules of thumb, or are based on plant factors other than empirically determined water use rates. Further questions and considerations come readily to mind. Are changing regional climatic conditions accounted for in these estimates and is the amount and timing of rainfall integrated in some meaningful way? Are the changing water holding capacities of different soil types accomodated? Over what period of time will this soil volume support the tree and where will the water come from? Are these methods based on whole water use rates and do they account for species and canopy size differences? It would also be very useful

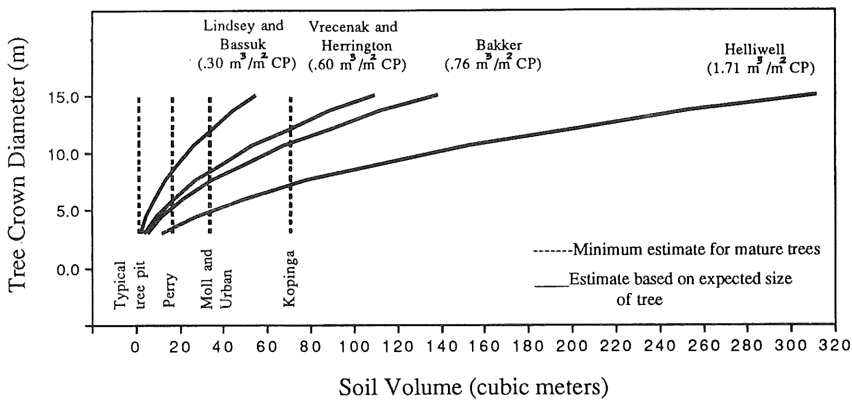

FIGURE 1. A comparison of recommended soil volume estimates. A typical tree pit is 1.8 m^3. HELLIWELL (1986) and VRECENAK and HERRINGTON (1984) estimates were reinterpreted by authors to relate to crown projection (CP). Crown projection is defined as the total surface area of the ground area under the dripline of a canopy. It is easy to measure and is frequently used as a way to quantitatively describe the canopy relative to some other measurement of plant growth or development.

if whole tree water loss estimations were standardized on one common plant parameter. Soil estimates could then be linked directly to this measurement. No one of these soil volume estimations really addresses all of these concerns.

Balancing water supply and demand with adequate soil volume

Water is added to the soil mainly through precipitation. An examination of modified climatic diagrams created for a range of British and Irish locations indicates that evaporation almost always exceeds precipitation during the period of greatest tree growth, May through October (Figure 2). Evaporation rises steadily over the growing season, peaking mainly in July, less frequently in June. Precipitation rises only slightly during this period, having already dropped significantly from higher winter rates (where significant soil water recharge occurs).

To compound this overall deficit, not all precipitation is particularly effective. While most of the moisture in the soil available to trees is obviously derived from precipitation, not all precipitation increases the soil moisture content in an equally effective manner. Significant amounts may be evaporated before they even reach the ground, intercepted by the canopy foliage, lost by surface runof, or percolated beyond the root zone (DAUBENMIRE, 1947; OKE, 1978; BELSKY *et al.*, 1990).

The important point here is that the proportion of known precipitation that actually becomes available for plant use is dependent on the pattern and intensity of rainfall, canopy size and structure, and the water holding and drainage capacities of the soil. Accurately estimating this amount for any defined period of time presupposes elaborate and detailed knowledge of both specific sites and individual trees, information which is not always readily obtainable.

The water that is remaining moves from the soil into the roots and up into the tree where almost all of it is evaporated as water vapour directly from the leaf surface in the process of transpiration (KRAMER, 1979). Transpiration occurs in response to increasing sunlight (duration and intensity), air temperature, wind speed and decreasing relative humidity. Collectively, these factors constitute atmospheric demand (ROSENBERG *et al.*, 1983). It is this demand, external to the tree, which subsequently can dictate the amount of water that must be taken up by the roots to replenish these losses. However water loss can be modified by various plant responses, especially stomatal closure, which occurs during periods of low soil water and high atmospheric demand. Likewise, while increased root density and root extension aid the tree in extracting more of the available water for a given soil volume, the rate at which the roots are able to take up water during these periods of high atmospheric demand is ultimately

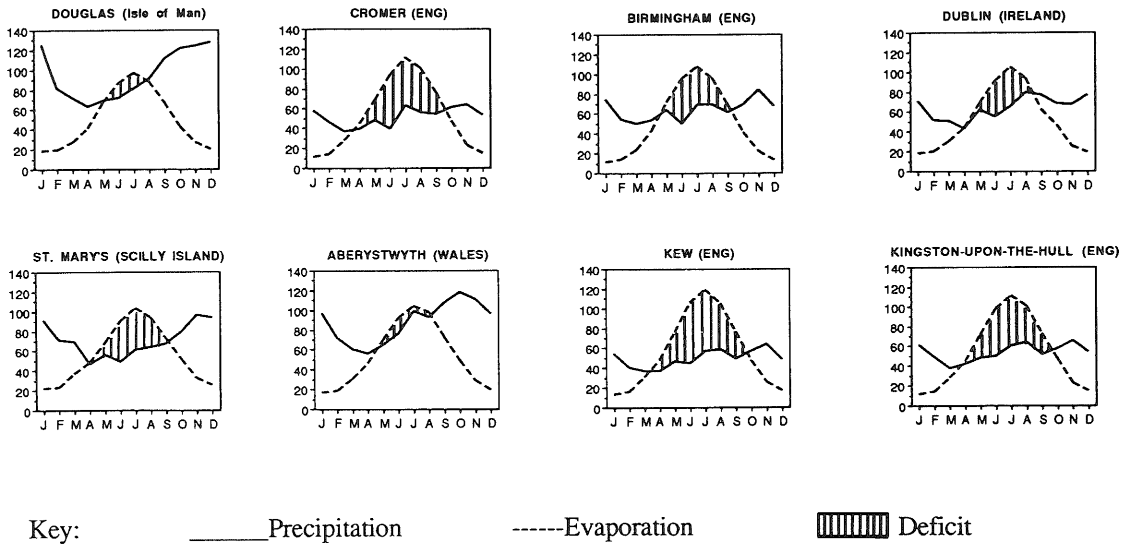

FIGURE 2. Climatic graphs of mean monthly precipitation and evaporation rates for ten British and Irish locations. These graphs were derived from data in MULLER (1982). The Y axis is in mm of precipitation and evaporation, the X axis is in months.

dependent on soil texture, structure, and volume (HILLEL, 1982; GLINSKI and LIPIEC, 1990). The water status of the tree at any given point then, is a function of this interaction between tree response to atmospheric demand, the amount of available water stored in the root zone at any given time, and the ability of the roots to draw this water up.

Conventional estimates of transpiration range from 132 L of water a day for a 10 m tall tree (VRECENAK and HERRINGTON, 1984) to 946 L a day for 19 m diameter tree of average density (KRAMER, 1987). By comparison a typical 1.2 m × 1.2 m × 1.2 m tree pit filled with a loam soil could hold approximately 25 L of water, which these trees would deplete quite quickly. Trees growing in these pits will fare poorly and die unless the roots are able to move out of this constraining volume of soil into amenable soils nearby.

Atmospheric demand is also greatly increased in the built environment, a harsh montage of reflective and absorptive surfaces such as roads, buildings, sidewalks, and cars. The subsequent release of stored heat from these surfaces leads to higher daytime and nighttime temperatures and lower relative humidites, hence the characterisation of the city as a "heat island" (CHANDLER, 1976; WHITLOW and BASSUK, 1987). These factors can elevate a tree's demand for water and greatly aggrevate the effects of already unfavorable growing conditions.

The overall objective of this method is to provide a soil volume sufficiently large enough to avoid water stress between expected precipitation or perhaps planned irrigation events. The assumption would be that recharge of the soil volume would occur during the intervening period.

Preliminary background research

In this current study, the relationship between evaporation and gravemetrically determined water loss from tree canopies was derived for a variety of tree species over two growing seasons in Ithaca, New York, U.S.A. These species were *Amelanchier* 'Robin Hill Pink', *Sophora japonica* 'Regent', *Tilia americana* 'Redmond', and *Fraxinus americana* 'Autumn Purple'. Readings were taken from a nearby U.S. Weather Bureau Class A evaporation pan. This pan is filled with water and a micrometer gauge measures daily water level changes. Typically evaporation from these pans integrates the major environmental influences governing transpiration. Free water evaporation from the surface of the pan was then equated with the evaporation of water from the surface of a leaf from the trees studied.

The results of this experiment yielded a significant correlation, whereby 85 per cent of the variability in whole tree water loss could be accounted for simply with knowledge of total tree canopy area and pan evaporation. Pan evaporation, therefore, was a significant predictor of whole tree water loss on a daily basis for a range of atmospheric conditions.

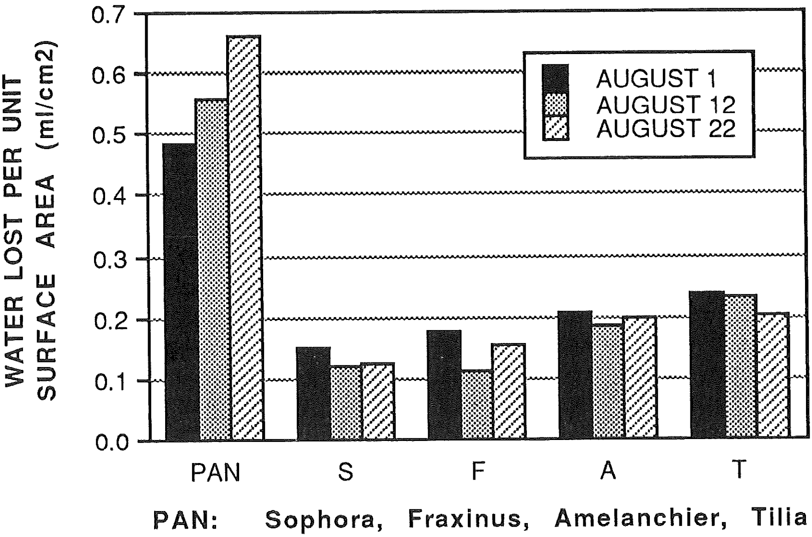

FIGURE 3. Evaporation from the pan compared with transpiration from the four tree species for a sampling of dates.

Whole tree water loss relative to pan evaporation was not significantly different for the four species. On any given day, water transpired from the trees averaged 30 per cent of the water evaporated from the pan (Figure 3). This figure represents optimal transpiration. In reality it may be lower because a tree has the ability to grow well even if only a percentage of its potential water need is being met. Whole tree transpiration increased only as overall canopy area increased, even though these four trees represent a gradient of leaf sizes from 5 to 46 cm^2. Though many studies discuss the possible effect of smaller leaf sizes on reduced water losses (LEWIS, 1972; SMITH, 1978; NOBEL, 1980; POTTS and HERRINGTON, 1982), in this study leaf or leaflet size was not a good predictor of water loss. It would appear then that individual correlations between each species and pan evaporation may not have to be established to describe accurately whole tree water loss.

Estimating whole tree water loss with evaporation data

Knowing now that there is a strong relationship between pan evaporation and whole tree water loss and that a tree is typically expected to lose only 30 per cent of what the pan loses, an even simpler way to estimate whole tree water use and calculate subsequent soil volumes was devised. Using evaporation data recorded from a Symons tank (representing 10 years of averaged data record) at the Kew research station in Great Britain, the process is presented here for a tree with 6 m of crown diameter.

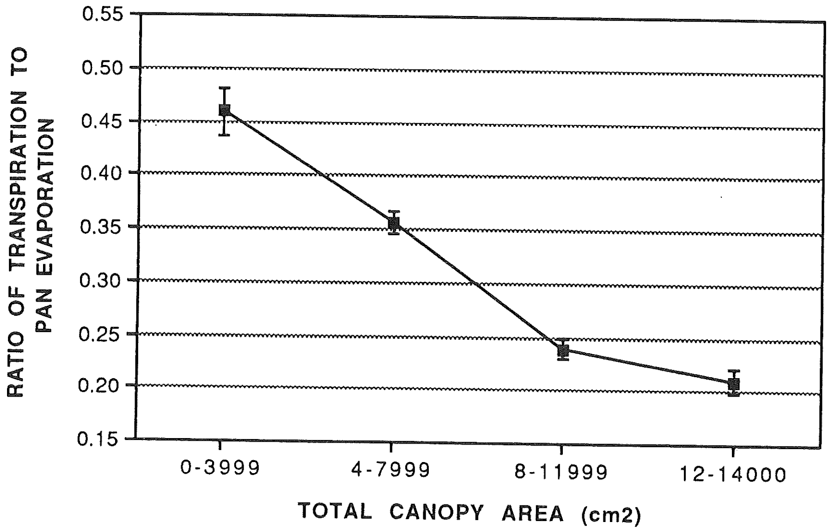

FIGURE 4. The change in the ratio of transpiration to pan evaporation as canopy size increases. All species are grouped. Standard errors as noted.

Step 1: Determine whole tree water loss

1. Calculate crown projection and select a leaf area index. Crown projection (CP) is simply the area under the trees' dripline, which is just the area of a circle [π (radius)^2]. Adjust this formula to use diameter instead, so that area equals (crown diameter)$^2 \times .785$. For this tree then, (6m)$^2 \times .785$ is 28.26 m^2 of CP. Now select a leaf area index (LAI), which is just the ratio of leaf surface area to CP. We will use a LAI of 4, where 4 is the average density of a tree of this size and shape. This means that the tree has a leaf area that is four times greater than the CP.

$$CP = 28.26\,m^2$$
$$LAI = 4$$

2. Climate. Determine the highest atmospheric demand. Select the value to use by looking up the highest mean monthly evaporation value for your location. For Kew it is 120 mm in July. This figure is divided by the number of days in the month (31) to yield a value for daily evaporation of 3.87 mm.

$$\text{Daily evaporation} = 3.87\,\text{mm}$$

3. Tree transpiration to pan ratio. Adjust for the fact that a cm^2 of leaf surface will not lose as much water as a cm^2 of the pan surface due to various plant and soil factors. Based on this research, a 20 per cent

adjustment factor is selected which states that a cm^2 of leaf transpires only about 1/5 as much as a cm^2 of pan surface (see discussion).

$$\text{Ratio} = .20$$

4. Now multiply all of this out to obtain daily whole tree water use:

CP		*LAI*		*Highest mean daily evaporation*		*Ratio*		*Daily tree water use*
28.26 m^2	×	4	×	3.87 mm	×	.20	=	87 L

Step 2: Estimate an adequate soil volume using the predicted daily water use of 87 L.

5. How long should the tree be able to go without water? A rainfree period of ten days is chosen. For trees in the ground, the assumption is that the calculated soil volume would hold sufficient water to carry the tree through this interval, after which recharge of soil water would occur through precipitation, irrigation, lateral soil water movement, or capillary rise from a water table. The 87 L is multiplied by 10 days to yield a total water demand of 870 L.

6. Available water holding capacity of the soil (AWHC). Choose a soil with a known AWHC. A silt loam with a capacity of 19.9 per cent is chosen. Therefore, 870 L is divided by .199 to yield a needed soil reservoir of 4.37 m^3. Given a crown projection of 28.26 m^2, this converts to .15 m^3 of soil per 1 m^2 of crown projection.

Step 3: Calculate possible bed dimensions

Assuming a depth of no more than 1 m, calculate a surface area to accomodate 4.37 m^3 of soil. This can be configured roughly as a 2.1 m × 2.1 m × 1 m depth bed or a 1.1 m × 4 m × 1 m depth bed.

The predicted daily water requirements and requisite soil volumes for this same tree are presented for six research stations scattered across Great Britain (Table 1). Along with this, the relationship of soil volume needed per unit area of crown projection has been calculated. For Britain, there is a great deal of similarity among these values and a generic estimate of .15 m^3 of soil per m^2 of crown projection could be used. For comparison, in the U.S.A., due to higher evaporative demand levels, the soil estimate would be about twice as much, .30 m^3 of soil per m^2 of CP. This is with omitting Phoenix, Arizona a city in the arid southwest which experiences exceptionally high evaporation and very low precipitation. This methodology might not work well for such areas because the volumes calculated would be prohibitively large, even more so since the intervals between

TABLE 1 Predicted water use rates and subsequent soil volumes for representative research stations in Great Britain and U.S. cities for a tree with a crown projection of 28.26 m^2

British Station[1]	Highest Mean Monthly Pan Evaporation (mm)(month)	Daily Tank Evaporation (mm)	Daily Water Use Rate (l)	10 Day Soil Volume (m^3)	Ratio: m^3 Soil/ m^2 CP
Lake Vyrnwy	80 July	2.58	58	2.91	.10
Rosewarne	83 June	2.77	63	3.16	.11
Otterbourne	96 July	3.10	70	3.52	.12
Ardsley	102 June	3.40	77	3.82	.13
Barrow Gurney	102 July	3.29	74	3.72	.13
Ormesby	107 July	3.45	78	3.92	.14
Wellesbourne	105 July	3.39	77	3.87	.14
Kew	120 July	3.87	87	4.37	.15
U.S. City[2]					
Ithaca, NY	158 July	5.10	117	5.89	.21
Seattle, WA	178 July	5.74	136	6.74	.24
Philadelphia, PA	181 July	5.84	136	6.80	.25
Los Angeles, CA	199 July	6.42	148	7.48	.26
Minneapolis, MN	200 July	6.45	151	7.56	.27
Miami, FL	204 July	6.58	155	7.73	.27
Witchita, KS	245 July	7.91	185	9.26	.32
Phoenix, AZ	377 June	12.57	284	14.24	.50

[1]Evaporation values obtained from a Symons tank (British Rainfall, 1967)
[2]Evaporation values obtained from a U.S. Weather Bureau Class A pan (Farmsworth and Thompson, 1982)

precipitation events will likely exceed ten days. It is doubtful that roots would be able to exploit effectively such extensive volumes for the tree's large daily water requirements.

Most importantly, for these volumes to work it should be strongly emphasized that tree pits, extended shared beds, and containers must be mulched. Soil water depletion through evaporation can, in general, be reduced by half or more if the ground treatment is an organic mulch rather than bare soil or grass (DAUBENMIRE, 1947; DAVIES, 1975).

Discussion: An overview of the methodology

The intent of this article is to provide a knowledgeable framework for both critically evaluating and effectively using the simplified soil volume methodology presented here. In the example given above, the decision at each step as to which number to use was summarily made for the arboriculturist. It is now appropriate to present discussion both on the rationale for the numbers chosen and what considerations would change these numbers.

A leaf area index (LAI) of 4 has been chosen, this being a common tree density for a deciduous tree of the size specified. Typically LAI's for deciduous trees range from 1 to 12, with the higher numbers indicating clumped leaves, and the lower numbers indicating low canopy density and leaf overlap. A great deal more research is needed to refine realistically LAI for a wide range of tree species, sizes and forms relative to crown projection.

The highest mean daily evaporation value has been used, conditions typically occuring in July in both Britain and the U.S.A. The arboriculturist may obtain these values for specific areas from the meterological publication, British Rainfall. July might be the month to target for supplemental irrigation, if at all. It will be at least 10–15 years before the tree reaches a size necessitating the full use of this soil volume. The implication is that this volume is self-supporting for this number of years, and when sufficient size has been reached, the tree's water supply needs to be assessed. At this point it should be determined if soil water recharge in sufficient amounts is occuring, or if supplemental irrigation needs to be applied.

Choosing an appropriate adjustment factor representing the ratio of tree water use to pan evaporation on a cm^2 basis was the result of several important considerations. Though the mean ratio for these four species growing under well watered conditions was empirically established as 30 per cent in the current study, 20 per cent was considered as a more realistic figure. This figure may seem low when compared with the ones already derived for other trees, such as 25–50 per cent for pecan (MIYAMOTO, 1983), 40–135 per cent for various fruit and nut trees (DOOREBOS and PRUITT, 1975), and 60–70 per cent for apples in a semi-arid region (LEVIN and ASSAF, 1973). It must be remembered though that these other values included evaporation from the ground surface as well, which was eliminated in this study. Secondly, it may be necessary to replace only a certain percentage of the predetermined potential water requirements of a tree. In the Netherlands, KOPINGA (1986) determined that even when actual growth was only 40 per cent of potential growth, an acceptable level of plant health and development was maintained for those species that are considered somewhat drought tolerant. A 75 per cent water replacement value is cited as the quantity necessary to maintain this acceptable growth rate. Thirdly, this study also showed that the ratio of transpiration to pan evaporation decreased rapidly with increasing canopy size, dropping to about 20 per cent in the larger trees (Figure 4). This is probably due to the effects of greater mutual leaf shading in these trees, which resulted in reduced water losses per cm^2 of leaf area. Therefore, while larger trees lose more water on a whole tree basis, they lose less per cm^2 of leaf area. This would indicate that as a tree canopy continues to mature, this ratio of 20 per cent could in fact be lower.

Finally, this ratio was established using a Class A pan, and it should be empirically re-established using the Symons tank. A Symons evaporation tank holds 2–1/4 times more water, and has three times the surface area as compared to the Class A Evaporation pan used in the experiment conducted in New York (HOUNMAN, 1973). The Class A pan also sits completely above the ground, while most of the Symons tank is sunk beneath the surface. These structural and siting differences will affect evaporation and subsequently alter this ratio if using evaporation data from the tank, though it does not appear as if it will alter it significantly. In a study of evaporation from the pan versus the tank at a range of sites in Great Britain, it was determined that the tank evaporated only about 8 per cent of the water from a pan on a cm^2 surface area (HOLLAND, 1961). This would mean perhaps that a ratio of 15 per cent rather than 20 per cent should be used.

How long the tree should be able to go without supplementary water is a very open-ended decision here, calling many factors into play. It is known that precipitation does not equal evaporation over the typical growing season, May through October, and a deficit is always in evidence, regardless of precipitation frequency and duration, and that only a percentage of actual precipitation is considered effective and available for tree use. Yet though evaporation rates greatly exceed transpiration rates, some soil water storage occurs from November to April, and for tree pits, some of this water could be assumed to be available. Since the critical months are June and July, the arboriculturist must decide if ten days is a reasonable period of time between rain events (it was for Ithaca, New York). Establishing the frequency of precipitation events that exceed 1/10″ or more during these two months would be helpful in determining an appropriate length of time period.

A silt loam was chosen, but obviously many factors are involved in the selection of the soil. Soils hold varying amounts of water depending on their texture and structure and only a certain percentage of that is actually available for tree uptake. Assuming there is an opportunity of specifying the soil type, a minimum of 12 per cent of the water should be held as available water, with optimum values approaching 20–25 per cent. In any case, the higher capacity soils should be selected. The larger the soil volume with a given available water-holding capacity, the more water the soil can hold, the longer a tree can go without water. At some point however, a tradeoff obviously exists; the finer soils may inhibit positive drainage and adversely affect aeration and a sufficiently large soil volume does not necessarily guarantee tree longevity if the drainage and aeration site qualities are poor. As with the current soil estimations however, large soil volumes are hard to obtain in urban areas. The objective should be to keep the volumes reasonably achievable and yet know what the limitations to that volume are, i.e. the tree can go approximately 10 days without sufficient rain or irrigation.

A further consideration regarding the soil volume involves accommodating large root systems. The field of forestry has provided a few relationships between stem diameter and root biomass (LANDSBERG, 1986). However much more study is needed to quantify root biomass for a range of ornamental trees, especially as it relates to crown width, in order to account adequately for it in the soil volume while increasing root mass can alter the aeration conditions of a soil for the worse in containers (BIRAN and ELIASSAF, 1980), it is not clear that this problem would occur in tree pits as well.

A final caveat concerns the reliability of using pan evaporation values that are not specifically tied to one urban site, where microclimatic conditions result in evaporation values that can be very different from weather station data (KALMA *et al.*, 1977; FELDHAKE *et al.*, 1983). Most evaporation values are now obtained from airports or research stations, areas typically outside of the city proper. Predicting the size of any given site specific "urban effect" is highly problematic. The built environment is complicated and atmospheric demand conditions are still largely unquantified. This methodology though, is meant to be a general approximation. More localized pan evaporation readings would be ideal but they are hard to obtain. Just as likely, informed and intuitive adjustments could be made in the field by the professional. If one suspects that a given planting site is subject to greater atmospheric demand than the pan evaporation values indicate, either larger evaporation values could be substituted, or a shorter rain/irrigation period could be specified.

Conclusion

Ultimately, planting strategies need to be thoughtfully revised. Ways of increasing possible rooting volume for trees at grade need to be further exploited. These include using interconnected tree pits that run parallel to the sidewalk and street. In grouped plantings, the large shared rooting space begins to approach the volumes which are needed by typical sized specimen trees, up to 5 m^3 of soil. Likewise, where roots grow and how fast they grow is most favoured by reasonably moist, fertile and well-aerated soil. If underground space is limited, plan root "break out" zones to accomodate additional root growth in contiguous areas outside the tree pit, such as in lawn areas or underneath specially constructed pervious pavers (EVANS *et al.*, 1990). When urban soils are totally unsuitable as a growing medium, planters or raised beds can be used just as effectively if realistic soil volumes for a given size tree at maturity are specified.

This methodology offers a simple yet highly accurate way to estimate supportive soil volumes that can be handily calculated in the field. Depending on the tree size selected, the period of time between irrigation events can be set to accomodate staffing levels. Importantly, it also allows work from the other direction. If given an existing volume of soil in a tree pit, vault or planter, the size of tree this volume will reasonably support can be decided. The use of this methodology has important implications for ensuring better survivability and development of trees growing in urban areas and hopefully will greatly enhance attempts to "green" cities and make them more humane, livable and aesthetically pleasing environments.

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