SPECIFICATION OF SOIL VOLUME AND IRRIGATION FREQUENCY FOR URBAN TREE CONTAINERS USING CLIMATE DATA

by Arthur T. DeGaetano

Abstract. Typically, limitations in soil volume deprive urban trees of water supplies adequate to meet evapotranspirational demand, resulting in suboptimal tree survival, health, and development. Proper sizing of urban tree containers can mitigate these unfavorable consequences. Current recommendations of appropriate soil volumes for urban trees are based on average climate conditions and therefore do not address daily and annual variations in weather. The method developed in this paper uses daily climatological data to estimate the soil volume necessary to provide some minimal amount of moisture during the driest growing season likely to be encountered during an urban tree's expected lifespan. This method allows a range of historic weather conditions to be taken into account. For example, in New York City, without irrigation a medium-sized tree (6-m [20-ft] crown diameter) grown in 17 m^3 (600 ft^3) of soil would face a water deficit (<50% available water capacity) every other year. When provided with 27.4 m^3 (967 ft^3) of soil, this tree would face a deficit only once in 10 years. If only 4.3 m^3 (152 ft^3) of soil volume can be supplied, such a tree, when irrigated approximately once every 5 days, would face a water deficit (<70% available water capacity) once in 10 years.

Key Words. Urban forestry; soil water content; plant/soil water relations; evapotranspiration; Penman-Monteith equation.

It is surprising that climate-based guidelines addressing adequate soil volumes and/or irrigation frequencies for established urban container-grown trees have not been developed. Among others, Lindsey and Bassuk (1992) cite inadequate underground rooting space as one of the main contributors to the premature mortality of urban trees. Typically, urban trees are planted in confined areas, either constrained by surrounding pavement and urban infrastructure or grown in isolated above- or belowground containers. Under such conditions, soil moisture often is limited due to soil compaction or restricted soil volume. These circumstances lead to recurrent and sometimes prolonged periods of water deficit because evapotranspirational demand often exceeds available water.

In engineering applications, the use of climate-based design specifications is widespread. These requirements ensure that the buildings and infrastructure that compose the urban environment are designed to withstand the variety of weather conditions they are likely to encounter during their expected lifetimes (e.g., DeGaetano et al. 1997; Wilks 1993). For instance, a stormwater drainage system is required to accommodate the volume of rainfall that occurs, on average, once every 50 years. Such rain events are said to have a 50-year return period. Using historical evapotranspiration and precipitation data, similar specifications for adequate soil volumes and/or irrigation frequencies for urban trees can be obtained.

To date, this type of climate-related information has not been rigorously compiled and therefore has not been applied. However, the utility of such information is threefold. Climate-based specifications would allow 1) appropriate soil volumes to be specified for a given location, 2) a schedule of irrigation to be developed in accordance with the available soil volume, and 3) the selection of species that are able to tolerate the water stress conditions likely to occur during their intended lifespan. It is the objective of this paper to describe a method by which climate-based soil volumes and/or irrigation frequencies for container-grown urban trees can be computed. The procedure is illustrated using examples based on plausible values of tree water use, canopy interception, and soil water-holding capacity. However, the robustness of the method allows for the use of more representative values of these variables in specific applications.

CURRENT PRACTICES

A variety of recommendations regarding the soil volumes adequate to support urban tree planting exist in the literature. Most often these recommendations are based on approximations or plant factors other than empirical water demand. For instance, Helliwell (1986) estimated that a tree with a crown diameter of

6.1 m (20 ft) requires more than 50 m^3 (1,764 ft^3) of soil. Vrecenak and Herrington (1984) suggested a more modest 18 m^3 (635 ft^3) soil volume for the same size tree. Lindsey and Bassuk (1992) contend that many of the volumes cited in the literature exceed those which would be possible under typical urban conditions.

Lindsey and Bassuk (1991) appear to have been the first to specify soil volumes for container-grown urban trees using climatological data. Soil volumes ranging from 6.2 m^3 (219 ft^3) to 15 m^3 (529 ft^3) were indicated for a tree having a 6.1-m (20-ft) crown diameter in most semi-arid (e.g., Denver) to humid U.S. climates. In an arid location such as Phoenix, the necessary soil volume increases to over 125 m^3 (4,400 ft^3). While Lindsey and Bassuk's method provides a fairly rigorous procedure for specifying adequate soil volumes, their use of average evaporation rates and the assumption of complete recharge by precipitation alone every tenth day compromise the accuracy of their results. To compensate for these shortcomings, a slightly different approach is developed and implemented in this paper. With this revised approach, the frequency at which moisture levels in the container fall below some predetermined threshold can be estimated. This approach allows container size to be specified not only for average conditions, but also for growing seasons with more extreme moisture deficits. Therefore, a container volume that matches the expected lifespan of the tree, rather than average conditions, can be selected. Furthermore, in cases for which the recommended container size is too large to be practical, it is possible to estimate the amount and frequency of irrigation necessary to compensate for the suboptimal container size.

COMPUTING DAILY WATER BUDGET

The procedure implemented in this paper uses Lindsey and Bassuk's (1991) method as a basis. As opposed to this earlier method, it relies on daily observed (rather than average) evaporation and rainfall data to compute the amount of available soil moisture within a container of given size. The process is iterative, allowing daily soil water to be estimated using the following 5-step procedure.

1. Choose an appropriate set of input parameters describing the tree, soil, and meteorological conditions. These variables include

a. The crown projection (CP) of the tree. This value describes the size of the tree that will be grown in the container and should be selected based on the diameter of the crown (the distance across the tree's dripline through the center of the tree) at maturity. The crown projection can then be computed using the equation 0.785 ∞ D^2, where D is canopy diameter. A tree with a diameter of 5.5 m (18 ft), would have a projection of 0.785 ∞ 30.25 m^2, which equals 23.7 m^2 (254 ft^2).

b. The leaf area index (LAI) for the tree under consideration. The LAI of deciduous trees in urban settings typically varies from 2 to 8, with the higher values indicating considerable leaf overlap (e.g., Peper and McPherson, 1998). Lindsay and Bassuk (1991) and Hitchmough (1992) adopted 4 as an appropriate LAI for urban trees. However, Hitchmough (1992) uses an LAI of 3 for trees with crown diameters <2 m (6.5 ft). For illustrative purposes, an LAI of 4 is adopted in this paper. In specific applications, a more representative LAI should be selected based on species, tree size, etc.

c. A set of historical daily evaporation rates (E_d) for the site. Daily observations of pan evaporation are taken at selected weather stations and can be obtained from the National Oceanic and Atmospheric Administration (151 Patten Ave., Asheville, NC). Unfortunately, historical records of pan evaporation data are usually short (<10 years) and tend not to be available for urban locations. However, daily pan evaporation data can be modeled using the modified Penman-Monteith equation (Monteith 1965). The necessary meteorological inputs to this equation, with the exception of solar radiation, are routinely measured at most commercial airports. A model described by DeGaetano et al. (1995) can be used to estimate solar radiation based on common observations of cloudiness, atmospheric pressure, humidity, and temperature. Comparisons of modeled versus observed pan evaporation indicate that, on average, the 2 values are equal. (DeGaetano et al. 1993). For most U.S. cities, model-derived daily evaporation rates are available from the author from 1948 through the present.

d. An appropriate pan factor (PF). Although pan evaporation is related to water loss from the tree, the pan value represents maximum possible evaporation. Lindsay and Bassuk (1992) showed that whole-tree water loss was between 20% and 45% of pan evaporation, with the higher value (45%) applicable to small canopies and during foliation. The 20% factor was representative of canopy diameters >1.2 m (4 ft) during the majority of the growing season in 4 species (Amelanchier 'Robin Hood Pink', Sophora japonica 'Regent', Tilia americana 'Redmond', and Fraxinus americana 'Autumn Purple'). Miyamoto (1983) cites a similar range in pan factor for pecan, as do Eastham et al. (1993) and George (1990) for several eucalypt species. Others have derived higher values in the range of 40% to 70% for fruit trees in arid climates (e.g., Levin and Assaf, 1973). The pan factor of 0.2 used by Lindsay and Bassuk (1992) is adopted for illustrative purposes in the paper, based on their field data and the data's specificity to urban trees. Clearly, other pan factors could be used in specific applications of this methodology, particularly if these values are supported by experimental observations.

e. The available (or potential) soil volume (S). This variable is simply the volume of soil held by the existing or a proposed container. If a container is designed to accommodate a specific return period, x, (i.e., container soil moisture is deficient, on average, once in x years), it may be necessary repeat the 5-step procedure using several different soil volumes to isolate that which corresponds to the desired return period. Conversely for an existing container, the measured container volume should be used.

f. The available water-holding capacity (AWC) of the soil. Only a portion of the total volume of soil in a planting container is available for water storage. This amount varies with soil texture and structure. Furthermore, all of the stored water is not available for tree uptake. The amount of water available is commonly referred to as the available water-holding capacity. Typically, AWC varies from 10 to 25% of the total soil volume (Cassell 1983). An AWC of 15% is used for illustrative purposes throughout this paper. This is typical of a loam soil.

2. Select a soil moisture deficit adjustment factor (DF). Because transpiration decreases in response to moisture stress, the daily evaporation rate must also be adjusted to account for soil moisture deficits. Using the relationship for deciduous trees given by Russell (1980) in conjunction with the modified Penman-Monteith equation, evapotranspiration from subsaturated soils can be expressed as a percentage of ET under freely available water conditions using the equation

$$DF = 0.82Z^2 + 0.20Z + 0.04.$$

Here, Z is the ratio of daily available water, W (described in Step 5), to the product $AWC \infty S$.

As an example, on a day when the soil contains only 50% of its available water storage (i.e., $Z = 0.5$), DF is approximately 0.3.

3. Compute the daily water loss (W_d). Once the previous variables have been identified for the tree and location under consideration, daily whole-tree water loss can be calculated using the equation:

$$W_d = CP \infty LAI \infty ET_d \infty PF \infty DF.$$

Assuming a 5.5-m (18-ft) canopy diameter, 6.4 mm (0.25 in.) of pan evaporation and the presence of 75% of the available soil moisture:

$$W_d = 23.7\ m^2 \infty 4 \infty 0.0064\ m \infty 0.2 \infty 0.6$$
$$= 0.073\ m^3\ (19\ gal).$$

4. Compute the effective daily rainfall (R_e). Historical daily rainfall records are available from the National Oceanic and Atmospheric Administration for most commercial airport locations. The total amount of rain that is measured does not all reach the container because a portion is intercepted by the tree canopy. Based on Helvey and Patric (1965) and Thompson et al. (1981), it is assumed that the first 2.54 mm (0.1 in.) of rainfall is trapped by the canopy. This agrees favorably with the values

given by Xiao et al. (1998) for a range of precipitation amounts in urban Sacramento. For cases in which the container extends beyond the canopy, interception affects only the portion of total rainfall that impinges on the canopy. Given the observed daily rainfall (R), the effective rainfall can be computed for cases in which the canopy extends beyond the container using

$$R_e = (R - 0.00254) \infty A.$$

where A is the surface area (m^2) of the container, R has units of meters, and it is assumed that at most 0.00254 m of rain is held by the canopy. R_e is constrained to values greater than 0.

If R_e exceeds the amount of available water storage, any excess water is not available to the tree and therefore is lost either as runoff (overflow) from the container or through leaching from the container bottom. As an illustration, consider a container that holds 4 m^3 (141 ft^3) of soil with an AWC 15%. This container can hold at most 0.6 m^3 (21 ft^3) of usable water. Due to prior daily water losses, only 75% of the available water (0.45 m^3) is present in the container. In this case, at most 0.15 m^3 (5.3 ft^3) of rain can be added to the container before the AWC is exceeded. If the container has surface dimensions of 2.1 ∞ 2.1 m (6.9 ∞ 6.9 ft), then effective rainfall in excess of 0.034 m (1.34 in.) would be lost. Here, the 0.034-m limit is obtained by dividing the maximum rainfall volume (0.15 m^3) by the container's surface area (4.4 m^2).

Any supplemental irrigation applied to the container is also considered effective rainfall.

5. Compute the daily available water (W) in the container. This value is obtained by subtracting the daily water loss (W_d) from the W computed for the previous day (W_{n-1}) and then adding R_e, such that

$$W = (W_{n-1} - W_d) + R_e.$$

Using W_d = 0.073 m^3 from Step 3, the container and soil specifications of Step 1, and given a rainfall of 22.5 mm (0.89 in):

$$\begin{aligned} W &= (0.45 \text{ m}^3 - 0.073 \text{ m}^3) + (0.02 \text{ m} \infty 4.4 \text{ m}^2) \\ &= 0.465 \text{ m}^3 (16.4 \text{ ft}^3). \end{aligned}$$

For deciduous trees, evapotranspiration is assumed to be minimal during the winter; thus, at the beginning of the growing season (e.g., May 1 in northern climates), the available water in the container can be assumed to be at a maximum. Therefore, on the first day of the growing season, W_{n-1} equals the maximum available water (AWC ∞ S). On subsequent days, steps 2 through 5 are repeated to obtain a value of W for each day. This process continues until W equals (0.1 ∞ AWC ∞ S). At this W, the soil moisture within the container approaches the tree's permanent wilting point (Kramer 1983). Because any remaining water in the container is unavailable to the tree, a year in which this moisture deficit is reached is classified as "dry." Allowing 10% of the available water to remain in the container is intended to compensate for the uncertainty involved in specifying the permanent wilting point and provides a conservative estimate of the necessary soil volume.

After the above procedure has been applied to all remaining years with available climatological data, the number of years classified as "dry" are counted and this tally used to establish an adequate container size. Table 1 gives some examples of possible outcomes using the 5-step procedure with climatological data for 1980 through 1989. Because the 9.6-m^3 (340-ft^3) soil volume becomes "dry" in 5 of the 10 years of data, this soil volume corresponds to a 2-

Table 1. Example of 10-year series of dry and non-dry* (nd) years for 3 soil volumes from which return periods are calculated.

	Soil volume (m^3)		
Year	9.6	12.5	14.2
1980	dry	dry	nd
1981	dry	nd	nd
1982	nd	nd	nd
1983	nd	nd	nd
1984	dry	nd	nd
1985	nd	nd	nd
1986	nd	nd	nd
1987	dry	dry	dry
1988	dry	nd	nd
1989	nd	nd	nd

*Non-dry years are years in which W did not reach the permanent wilting point.

year return period. A tree planted in this volume of soil would, on average, face a severe moisture deficit every 2 years, and thus the expected rate of tree mortality would be high. In fact, using the 2-year return period soil volume, it would be reasonable to anticipate replacement of this tree every other year. Clearly, such a high rate of tree failure is unreasonable. However, if this determination is made before planting (or the design or purchase of the container), the container-sizing procedure can be used to determine a soil volume that will sustain the tree for a more reasonable period of years. Here, increasingly large soil volumes can be substituted in step 1e and the tally of "dry" years recomputed until an acceptable return interval is achieved.

If a 12.5-m^3 (440-ft^3) soil volume is chosen in Step 1e, the container becomes "dry" only twice in 10 years (Table 1). This soil volume corresponds to the 5-year return period. On average, the replacement of a tree grown in this soil volume should be expected every five years if supplemental irrigation is not provided. When the soil volume is further increased to 14.2 m^3 (500 ft^3), the container becomes "dry" only once in the 10-year period (Table 1). This soil volume corresponds to a 10-year return period moisture deficit. Similar, but more reliable, container sizes for these return periods can be obtained using a longer period of record. If 50 years were used, the 10-year return period container size would have gone "dry" 5 times during the 50-year period, while "dry" conditions would have occurred during approximately 25 years in the container holding the 2-year return period soil volume.

Certainly these soil volume specifications depend on the canopy size, LAI, pan factor, and AWC that are used to compute the daily water loss. While the literature suggests that the values that have been used as examples for these parameters are representative of typical urban tree species, values more characteristic of a particular species or soil condition can be substituted (if available) in individual cases.

Likewise, for many applications and species the definition of "dry" (10% of AWC) used in the previous set of examples is too lenient. Practically, the occurrence of such water deficits and variations in soil moisture content would lead to suboptimal growth and aesthetic quality (Kramer 1983). To account for this and to allow the procedure to be used with species less tolerant of moisture stress, a set of adjustment curves was developed (Figure 1). These curves relate the return period soil volumes obtained for a 10% of AWC minimum water content to the soil volume that would be required to maintain the water content of the container at levels ranging from 20% to 80% of AWC. For example, suppose a soil volume of 5 m^3 (176.5 ft^3) was indicated for some return period using the 10% of AWC "dry" threshold. Maintaining the available water in the container at a level >50% of AWC would require more than 20 m^3 (706 ft^3) of soil, based on Figure 1.

DETERMINING IRRIGATION FREQUENCY

In addition to being used to size containers, the above procedure can be used to specify irrigation frequency for a given soil volume. When soil volume cannot be made large enough, it is useful to determine how frequently the tree will require irrigation to survive its intended lifespan. In other cases, the work load required to regularly irrigate the tree, rather than soil volume, may be a more important consideration for trees that will receive routine care through their lives.

To determine these frequencies, the previous 5-step procedure is used. However, instead of counting "dry" years, the soil moisture is brought back to the

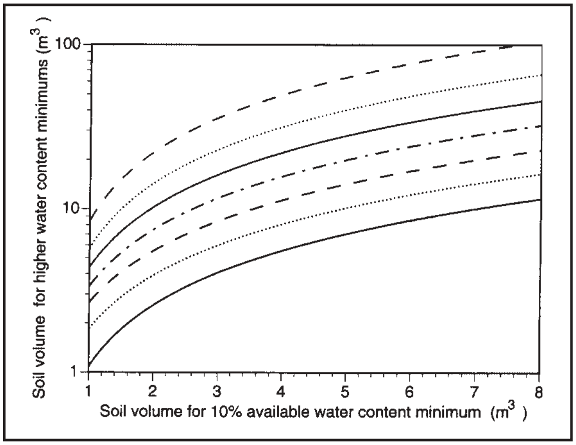

Figure 1. Conversion between soil volumes required to maintain a water content of 10% of AWC and those necessary to maintain water contents of 20% (solid black), 30% (dotted black), 40% (dashed black), 50% (dash-dotted black), 60% (solid gray), 70% (dotted gray), and 80% (dashed gray).

available capacity through irrigation whenever the soil moisture deficit in the container reaches the permanent wilting point. Irrigation is simulated by substituting R_e with 0.9 ∞ AWC ∞ S in step 5. This product represents the volume of water required for restore the soil to its maximum available water content. From this point, W continues to be computed daily through the remainder of the growing season and irrigation “applied” if indicated. For each year with available data, the number of irrigation applications is tallied, yielding a set of seasonal irrigation frequencies. For example, during 1988, irrigation may have been required 20 times for a given container size, while during 1989 the same soil volume required only 10 irrigations. Given the labor required to regularly irrigate the tree, it is likely that soil moisture levels would be kept near a level that promotes optimal health and aesthetic quality, rather than merely tree survival. Kopinga (1985) suggested that maintaining the soil moisture at 75% of the AWC was sufficient to meet this goal. Thus, a definition of “dry” more in line with Kopinga’s 0.75 ∞ AWC was adopted when specifying irrigation frequency.

CAUTIONARY NOTES

Several precautions should be considered when implementing these procedures. In addition to the assumptions regarding interception amount, and the relationship between pan evaporation and whole-tree water loss, it has also been assumed that container recharge is limited to precipitation and irrigation. Horizontal movement of water into the container (i.e., runoff into a subsurface vessel) is ignored, and it is assumed that roots are totally confined within the container. Therefore, subsurface water sources are also ignored. Soil evaporation also has been ignored. Such an omission is feasible when the container has been mulched. However, arguably, the presence of mulch will also limit the effective precipitation reaching the soil.

In practice, the assumptions used to illustrate the procedure in this paper can be modified to more accurately represent specific species and growing conditions. In fact, provided adequate information concerning the water-use requirements of 2 different species (i.e., species-specific pan factors), it would be possible to use the procedure to select the species best suited for a particular location. Such a decision should be based on arborcultural and economic considerations. For instance, suppose species A costs $20 per tree, while species B costs $40. Based on differences in water use, assume the soil moisture of the container supporting A falls below the permanent wilting point once in 6 years, while the same soil volume supporting B dries below this level once in 10 years. Over a 30-year period, species A would require replacement 5 times, while species B would need to be replaced only 3 times (assuming a water deficit below the permanent wilting point results in the loss of the tree). Because replacing species A five times costs $100, while replanting B three times costs $120, the choice of species A is economically justified.

Assumptions related to the minimum level of available soil moisture are addressed by Figure 1, which provides a means for converting the soil volume obtained for the (0.1 ∞ AWC ∞ S) soil moisture minimum to the volume necessary to maintain progressively higher soil moisture levels. DeGaetano and Hudson (2000) provide similar adjustments for different interception amounts and pan factors. These curves can be used to quantify the sensitivity of container size to the assumptions used here. They also can be used to convert the container specifications presented in the following section to those based on a different set of case-specific assumptions.

In most cases, the meteorological parameters upon which these specifications rely are measured at stations some distance away from the site of interest. It is likely that microclimatic conditions differ between the usual airport location of these measurements and urban street level.

CONTAINER SIZE EXAMPLES

Soil volumes corresponding to different return periods for trees having a range of crown diameters and irrigation schedules are given in Table 2. As expected, evapotranspiration and hence soil volume increases with increasing crown size, with this difference decreasing as irrigation frequency increases. Except for the smallest crown, where LAI = 3, an LAI of 4 is assumed. In all cases, 15% of the soil volume was assumed to be available for water storage. Climatological data for the period 1948 through 1997 at Boston, Massachusetts, were used to compute the container sizes.

In addition to the differences that resulted from crown diameter and irrigation frequency, soil volume

Table 2. Soil volume specifications (m^3) corresponding to 2-, 5-, 10-, 25-, and 50-year return period water deficits at Boston, Massachusetts. Specifications are given for a range of crown diameters (m) and irrigation frequencies. Possible surface dimensions (m) for a 1-m-deep container, corresponding to the 10-year return period soil volume, are given for reference.

Crown diameter	Irrigation interval	Return period					Possible surface dimensions
		2 yr	5 yr	10 yr	25 yr	50 yr	
2	none	0.5	0.6	0.6	0.8	0.8	1.0 ∞ 0.6
4	none	2.5	3.1	3.6	3.9	4.2	2.0 ∞ 1.8
6	none	5.4	7.1	8.0	8.8	9.3	2.0 ∞ 4.0
8	none	9.6	12.5	14.1	15.6	16.5	3.0 ∞ 4.7
2	once*	0.4	0.4	0.5	0.5	0.5	1.0 ∞ 0.5
4	once*	2.0	2.3	2.6	2.7	2.8	2.0 ∞ 1.3
6	once*	4.4	5.2	5.7	6.0	6.2	2.0 ∞ 2.9
8	once*	7.8	9.2	10.1	10.6	11.0	3.0 ∞ 3.4
2	monthly	0.4	0.5	0.5	0.6	0.6	1.0 ∞ 0.5
4	monthly	2.0	2.5	2.6	3.0	3.1	1.5 ∞ 1.7
6	monthly	4.5	5.4	5.8	6.6	6.9	1.5 ∞ 3.9
8	monthly	8.0	9.7	10.2	11.8	12.2	2.0 ∞ 5.1
2	bi-weekly	0.3	0.3	0.3	0.3	0.3	1.0 ∞ 0.3
4	bi-weekly	1.5	1.7	1.7	1.8	1.8	2.0 ∞ 0.9
6	bi-weekly	3.3	3.7	3.8	3.9	4.0	1.5 ∞ 2.5
8	bi-weekly	5.9	6.6	6.8	7.0	7.1	2.0 ∞ 3.4
2	weekly	0.3	0.3	0.3	0.3	0.3	0.5 ∞ 0.6
4	weekly	1.0	1.0	1.1	1.1	1.1	0.6 ∞ 1.8
6	weekly	2.2	2.3	2.4	2.4	2.4	1.5 ∞ 1.6
8	weekly	3.8	4.0	4.2	4.2	4.3	2.0 ∞ 2.1

*Irrigation applied at the first occurrence of water content -15% of AWC.

specifications also vary with respect to the ambient climate conditions to which a tree is exposed. Figure 2 addresses some of this variability for 5 U.S. sites east of the Mississippi River. These sites were chosen because they are among the largest urban areas in the country. Although the soil volume specification procedure is equally applicable for other large cities in the western United States (e.g., Denver or Los Angeles), in these areas unrealistic soil volumes would be required to support trees given only the natural rainfall. Likewise, the procedure is applicable in locations outside of the United States, provided the requisite meteorological data are available.

Along the northeast U.S. coast, geographic location has little effect on container size. Here similar soil volumes are specified for Boston, New York City, and Washington DC, despite a 4°C (39.2°F) increase in average summer temperature from Boston to Washington. Along this portiopn of the East Coast, the southward increase in temperature is complemented by a 1.27-cm (0.5-in.) increase in May through September precipitation. Similar container sizes are also specified at Chicago. Although Chicago averages 4.45 cm (1.75 in.) less summer precipitation than Washington, evapotranspiration is also reduced given that the average May through September temperature in Chicago is 3.8°C cooler (38.8°F) than in Washington. It is also likely that differences in rainfall frequency between Chicago and the East Coast cities influence the container sizes.

At Atlanta, the specified container size is consistently 18% larger than the other cities. This agrees with Lindsey and Bassuk's (1992) recommendations that show an increase in container size from Philadelphia to Miami. Based on these results, the values given in Table 2 should be applicable to cities in the Great Lakes, Midwest, Northeast, and Middle Atlantic regions of the United States. The Boston values can also be applied to Atlanta, provided they are increased by 18%.

IRRIGATION FREQUENCY EXAMPLES

Irrigation frequency specifications for 2 different tree sizes are given in Table 3. In all cases it is assumed that irrigation is required when the soil moisture level falls to 70% of the AWC. Climatological data for the 5 eastern U.S. cities in Figure 2 are used in this example, which assumes that AWC equals 15% of the soil volume, a pan factor of 0.2, and an LAI of 4 for the larger crown diameter. An LAI of 3 is used for the smaller tree.

The values in Table 3 can be put into perspective by assuming that irrigation is required from mid-April through mid-October. Thus, irrigation every day would correspond to an irrigation frequency of 183 days per season. Similarly, an irrigation frequency of 26 days per season corresponds to a weekly watering interval. Based on Table 3, if it were necessary for a tree with a crown diameter of 6 m (19.7 ft) to be grown in a limited soil volume of 2.6 m^3 (92 ft^3), supplemental irrigation would need to be applied approximately 110 times, on average, during the growing season. For perspective, such a container could have a surface area of 1.5 ∞ 1.7 m (4.9 ∞ 5.6 ft) and a depth of 1 m (3.3 ft) These conditions would be quite labor intensive because water would have to be applied on average every 1.7 days. Conversely, relatively moderate soil volumes in the range of 7.7 to 17 m^3 (272 to 600 ft^3) would require irrigation at 7- to 14-day intervals to support a tree with this crown diameter. If the containers holding these volumes of soil were 1 m (3.3 ft) deep, the surface dimensions of the smaller container might be 2.6 ∞ 3 m (8.5 ∞ 9.8 ft), while the larger container's surface might measure 4 ∞ 4.25 m (13.1 ∞ 13.9 ft). For the smaller tree, irrigation frequencies similar to those for the larger tree are obtained with nearly 10 times less soil volume (Table 3).

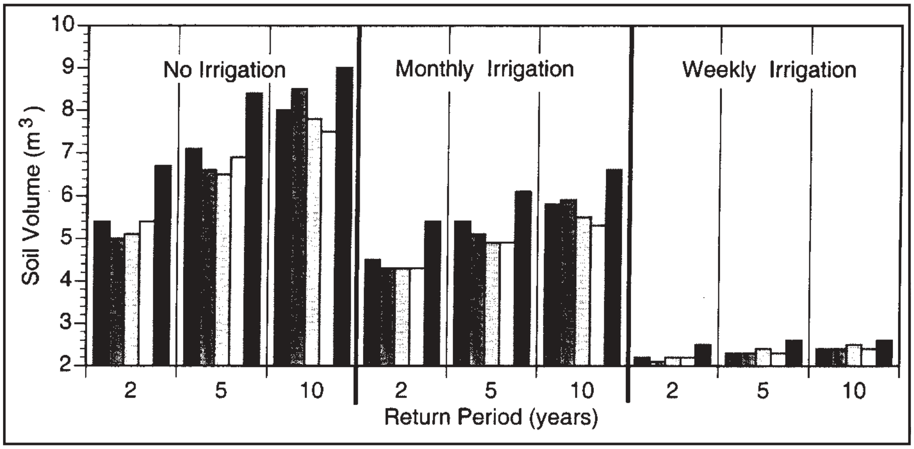

Figure 2. Soil volume specifications (m^3) corresponding to 2-, 5-, and 10-year return period water deficits at Boston, Massachusetts; New York, New York; Washington, DC; Chicago, Illinois; and Atlanta, Georgia. Station order corresponds to the sequence of bars, with Boston given by the leftmost bar, Chicago by the white bar, and Atlanta by the rightmost black bar. For each station and return period, soil volumes are specified for containers that are 1) never irrigated, 2) irrigated to AWC monthly, and 3) irrigated to AWC weekly. At all stations, a 6-m canopy diameter is assumed.

Table 3. Irrigation frequency specifications (days yr^{-1}) corresponding to 2- and 10-year return period water deficits at Boston (BOS), New York (LGA), Washington (DCA), Chicago (ORD), and Atlanta (ATL). Specifications are given for a range of soil volumes (m^3) and small and medium tree crown diameters (m).

Crown	Soil	2-year return period					10-year return period				
diameter	volume	BOS	LGA	DCA	ORD	ATL	BOS	LGA	DCA	ORD	ATL
6	2.6	93	97	103	93	111	100	110	114	108	123
6	7.7	27	27	29	25	31	30	32	34	30	36
6	17.0	10	10	10	9	11	12	12	13	12	14
6	23.8	6	5	7	5	7	8	8	8	8	9
2	0.17	107	115	120	108	127	117	123	129	121	136
2	0.60	28	29	31	27	34	32	33	36	33	38
2	1.28	11	10	12	10	13	13	13	15	13	14
2	1.87	6	5	7	5	7	8	8	8	8	10

SUMMARY

The procedure discussed in this paper provides a reliable method to specify soil volumes consistent with the expected lifespans of urban container-grown trees. The method uses daily evapotranspiration and precipitation data to characterize the water budget of the rooting zone. During each year, the soil volume necessary to provide some minimum quantity of available water is determined from the daily budget. Based on this multi-year distribution of minimum soil volumes, container sizes consistent with the intended life of the tree can be specified. Such return-period-based specifications are commonly used in engineering design applications.

The specification method is flexible enough to consider a variety of tree sizes and soil conditions. In addition, realizing that in many instances providing the recommended soil volume is not feasible, the method can be used to determine the appropriate time interval between irrigations. Such information is useful to ensure optimal tree health and aesthetic quality and can be used as a guide to determine staffing levels. Likewise, if supplemental irrigation will not be provided, the method can be used to determine the size of tree that can be supported by a predetermined soil volume.

The information on soil volume, lifespan (return period), and irrigation frequency can be used as an integral part of an economic decision-making process. In this example, if a soil volume is predetermined, an urban forester can weigh the costs of providing irrigation at the specified frequency against the costs of premature tree replacement. Clearly, the use of this climate-based method has multiple benefits. It provides a tool for horticultural professionals to manage both economic and human resources while ensuring that tree health is not compromised. Moreover, by promoting favorable tree growth, use of scientifically derived soil volumes should enhance the aesthetic quality and habitability of urban environments.

LITERATURE CITED

Cassell, D.K. 1983. Effects of soil characteristics and tillage practices on water storage and its availability to plant roots, pp 167–186. In Raper, C.D., and P.J. Kramer (Eds.). Crop Reactions to Water and Temperature Stresses in Humid Temperate Climates. Westview Press, Boulder, CO

DeGaetano, A.T., K.L. Eggleston, and W.W. Knapp. 1993. Operational modeling of regional soil moisture conditions in the northeastern United States. Proc. Eighth Conf. on Applied Climatology, American Meteorological Society, Boston, MA, pp. 28–31.

DeGaetano, A.T., K.L. Eggleston, and W.W. Knapp. 1995. A comparison of daily solar radiation estimates for the northeastern United States using the Northeast Regional Climate Center and National Renewable Energy Laboratory Models. Sol. Energy 55(3):185–194.

DeGaetano, A.T., and S.R. Hudson. 2000. Climate-based specification of soil volume and irrigation frequency for urban trees. J. Urban Plann. Devel. [Submitted].

DeGaetano, A.T., D.S. Wilks, and M. McKay. 1997. Extreme-value statistics for frost penetration depths in northeastern United States. J. Geotech. Geoenviron. Eng. 123(9):828–835.

Eastham, J., P.R. Scott, and R.A. Steckis. 1993. Evaluation of Eucalyptus camaldulensis (river gum) and Chamaecytisus proliferus (tagasaste) for salinity control by agroforestry. Land Degrad. Rehab. 4:113–122.

George, R.J. 1990. Reclaiming sandplain seeps by intercepting perched groundwater with Eucalypts. Land Degrad. Rehab. 2:13–25.

Helliwell, D.R. 1986. The extent of tree roots. Arboric. J. 10:341–347.

Helvey, J.D., and J.H. Patric. 1965. Canopy and litter interception of rainfall by hardwoods of eastern United States. Water Resour. Res. 1:193–206.

Hitchmough, J. 1992. Calculating the earth. Landscape Des. 270:42–44.

Kopinga, J. 1985. Research on street tree planting practices in the Netherlands. Proc. Fifth Annual METRIA Conference. Pennsylvania State University, University Park, PA.

Kramer, P.J. 1983. Water Relations of Plants. Academic, New York, NY. 489 pp.

Levin, I., and R. Assaf. 1973. Deciduous fruit trees, pp 404-409. In Yaron, B. E. Danfors, and Y. Vaadia (Eds.). Arid Zone Irrigation. Springer-Verlag, New York, NY.

Lindsey, P., and N. Bassuk. 1991. Specifying soil volumes to meet the water needs of mature urban street trees and trees in containers. J. Arboric. 17(6):141–148.

Lindsey, P., and N. Bassuk. 1992. Redesigning the urban forest from the ground below: A new approach to specifying adequate soil volumes for street trees. Arboric. J. 16:25–39.

Miyamoto, S. 1983. Consumptive water use of irrigated pecans. J. Am. Soc. Hortic. Sci. 108(5):676–681.

Monteith, J.L. 1965. Evaporation and environment. Symp. Soc. Exp. Biol. 19:205–234.

Peper, P.J., and E. G. McPherson. 1998. Comparison of five methods for estimating leaf area index of open-grown deciduous trees. J. Arboric. 24(2):98–111.

Russell, G. 1980. Crop evaporation, surface resistance and soil water status. Agric. Meteorol. 21:213–226.

Thompson, N., I.A. Barrie, and M. Ayles. 1981. The Meteorological Office Rainfall and Evaporation Calculation System (MORECS). United Kingdom Meteorological Office Hydrological Memorandum No. 45, 72 pp.

Vrecenak, A.J., and L.P. Herrington. 1984. Estimation of water use of landscape trees. J. Arboric. 10(12):313–319.

Wilks, D.S. 1993. Comparison of three-parameter probability distributions for representing annual extreme and partial duration precipitation series. Water Resour. Res. 29(10):3543–3549.

Xiao, Q., E.G. McPherson, J.R. Simpson, and S.L. Ustin. 1998. Rainfall interception by Sacramento's urban forest. J. Arboric. 24(4):235–244.

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Résumé. Typiquement, les limitations de volume de sol privent les arbres urbains de réserves en eau adéquates pour rencontrer leur demande en évapotranspiration, ce qui résulte en un taux de survie, une santé et un développement en deçà de leur optimum. Une bonne dimension de fosse de plantation ou de bac peut atténuer ces conséquences défavorables. Les recommandations usuelles sur le volume approprié de sol pour les arbres urbains sont basés sur des conditions climatiques moyennes et ne sont donc pas appropriées aux variations journalières et annuelles du temps. La méthode élaborée dans cet article utilise des données climatiques quotidiennes pour déterminer le volume de sol nécessaire pour fournir une quantité minimale d'humidité durant chacune des séries de croissance saisonnière. Ceci permet de tenir compte des marges de variations historiques de climat. Pour la ville de New York par exemple, un arbre de moyenne dimension croissant dans un volume de sol de 17,0 m^3 qui n'est pas irrigué ferait face à un déficit en eau (<50% de volume d'eau disponible) à toutes les années. Lorsque l'arbre dispose de 27,4 m^3 de sol, il ne subirait un déficit en eau qu'une année sur 10. Si seulement 4,3 m^3 sont disponibles, un tel arbre, lorsque irrigué une fois aux cinq jours environ, ne subirait un déficit en eau (<70% de volume d'eau disponible) qu'une fois aux 10 ans.

Zusammenfassung. Beschränkungen des Bodenvolumens entziehen Stadtbäumen das nötige Wasser, um mit der Verdunstungsrate Schritt zu halten, was dazu führt, daß das Überleben der Bäume, ihre gesundheit und Entwicklung suboptimal bleiben. Eine angemessene Größe der Pflanzlöcher und Container kann diese unerwünschten Konsequenzen mildern. Gegenwärtige Empfehlungen für eine angemessenes Bodenvolumen von Stadtbäumen basieren auf durchschnittlichen Klimabedingungen und können daher nicht tägliche und jährliche Klimaschwnkungen berücksichtigen. Die in dieser Studie vorgestellte Methode verwendet tägliche klimatologische Daten um das Bodenvolumen zu bestimmen, welches während einer Serie von Wachstumsperioden das erforderliche Minimum an Feuchtigkeit liefert. Das gestattet, die Bandbreite der historischen Wetteraufzeichnungen mit in Betracht zu ziehen. Zum Beispiel in New York würde ein mittelgroßer Baum in einem 17 cbm großen Pflanzloch ohne zusätzliche Bewässerung jedes zweite Jahr ein Wasserdefizit von mehr als 50 % erleiden. Wenn ein 27,4 cbm großes Pflanzloch zu Verfügung stünde, würde der Baum nur alle zehn Jahre unter einem Defizit leiden. Wenn nur ein 4,3 cbm großes Pflanzloch vorhanden wäre, würde ein solcher Baum bei einer Bewässerungsrate von jedem fünften Tag ein Bewässerungsdefizit von mehr als 70 % alle 10 Jahre einmal erfahren.

Resumen. Típicamente, las limitaciones en el volumen de suelo privan a los árboles urbanos de las aportaciones de agua que sean adecuadas a la demanda de evapotranspiración, resultante en una supervivencia, salud y desarrollo del árbol abajo del óptimo. El tamaño apropiado de la cepa y de los árboles urbanos puede mitigar estas consecuencias desfavorables. Las recomendaciones actuales de volúmenes apropiados de suelo para los árboles urbanos están basadas en condiciones promedio del clima y por lo tanto no responden por variaciones diarias y anuales del clima. El método desarrollado en este reporte usa datos climatológicos diarios para determinar el volumen de suelo necesario para proveer la cantidad mínima de humedad durante una serie de estaciones de crecimiento. Esto permite que sea tomado en cuenta el rango de condiciones históricas del clima. Por ejemplo, en la ciudad de New York, un árbol de tamaño medio sin riego creciendo en 17 m^3 (600 pies^3) de suelo haría frente a un déficit de agua (<50% de capacidad de agua disponible) cada dos años. Cuando se le provee con 27.4 m^3 (967 pies^3) de suelo este árbol solamente enfrentaría un déficit una vez en diez años. Si solamente 4.3 m^3 (152 pies^3) de volumen de suelo puede ser suplido, tal árbol, cuando es regado aproximadamente una vez cada cinco días, haría frente a un déficit de agua (<70% de capacidad de agua dispoible) una vez en 10 años.