EVALUATION OF A PAN EVAPORATION MODEL FOR ESTIMATING POST-PLANTING STREET TREE IRRIGATION REQUIREMENTS

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Abstract. Budget restraints force many cities to rely on volunteers for street tree irrigation. Reliable, easy to follow recommendations are needed. Using a pan evaporation model created by others, we developed a method for predicting irrigation amount and frequency for street trees and tested it on mulched, 3-in (7.5 cm) caliper, balled and burlapped *Pyrus calleryana* 'Redspire' (pear) and *Betula nigra* 'Heritage' (birch) trees five months after planting. The model predicted that root balls should be saturated every 3 days with 10 gal (38 l) of water. When tested against control trees which were irrigated on an "as needed" basis according to root ball moisture sensors, model trees required a total 130 gal (494 l) each of water, while pear and birch controls required an average of 108 and 122 gal (410 and 464 l) each, respectively, over the experimental period of two months. However, pear and birch controls required 25 and 24 site visits respectively, whereas model trees required only 13 visits. Refitting the model assumptions with actual tree measurements and adjusting the root ball soil tension point at which root balls were to be irrigated to well above the permanent wilting point, resulted in a 5 gal (19 l), every 3 day regime.

Introduction

Arborists are acutely aware of the need for maintaining proper soil water relations during tree establishment, particularly in urban areas where site conditions can dramatically increase daily transpiration and water use. However, until recently, little has been done to scientifically quantify water requirements of recently planted street trees. As a result, municipal foresters and landscapers typically provide only general recommendations, such as "irrigate frequently during dry periods" or "irrigate weekly during the first year" to crews or residents seeking post-planting watering tips. Current budget restraints require that many cities recruit nearby homeowners to irrigate newly planted street trees. Without specific and easily followed instructions, homeowners often irrigate only when leaves wilt or scorch, and trees are already under considerable stress at this time. Irrigation is often excessive after this point, as frantic homeowners make too-frequent water applications to visibly affected, yet seemingly unresponsive trees. Stress is exacerbated as soil oxygen needed for normal respiratory function is temporarily displaced from the saturated soil. The net effect of this type of reactive watering approach can be a prolonged establishment period, reduced growth and vigor, and abnormally high mortality rates, often attributed to "transplant shock" rather than poor irrigation practices.

A newly planted street tree, moved balled and burlapped (B&B), may have only 5% of its original root system length to supply water to the entire tree (4). Water stress at transplanting is a major factor responsible for poor establishment (5) and disease predisposition (15). Root growth during the first growing season after transplanting, especially early in the season, may be minimal on some species (6). Favorable root ball water relations are therefore of paramount importance during the first year of establishment.

In urban sites, evaporative demand is high (16), but water movement into root zones is usually disrupted (3). As a result, street trees may be highly dependent on irrigation, whereas their rural counterparts may more easily exist on rainfall. In Seattle, where only 18% of the annual rainfall is received during the growing season, failure to irrigate newly transplanted street trees can result in survival rates as low as 20%. Survival rates approach 100%, however, when trees are irrigated for the first two years (2).

Although some estimates have been made of whole tree water loss by individual trees (reviewed by Lindsey and Bassuk (10)), little or no published research has quantified the post-planting water requirements of street trees during establishment. The difficulty in directly measuring whole-plant transpiration has historically favored the use of more indirect methods which utilize meteorological data such as temperature and relative humidity to estimate evapotranspiration in agricultural crops. However, attempts to apply these formulas to determine transpiration rates of individual trees have been largely unsuccessful. One useful method for determination of evapotranspiration (ET) is the evaporation pan (14). The evaporation pan measures daily water level changes in a large pan of water as a result of evaporation. Atmospheric factors which influence evapotranspiration also influence water loss in the evaporation pan, and actual crop ET can be indexed against pan evaporation for future calculations.

Total leaf area and pan evaporation may account for as much as 85% of the variability of whole tree water loss (9). Knox (8) and Lindsey (9) found a strong correlation between transpiration rates and pan evaporation for several woody species. Lindsey and Bassuk (10) found that transpiration rate of larger trees was 20% that of pan evaporation. Ponder *et al.* (12) found no significant difference in growth between trees irrigated at rates equaling 25% of pan evaporation over those receiving higher amounts.

Assuming minimal evaporative loss of soil water through mulch and minimal water movement into the root ball across the root ball:backfill interface, the daily whole-tree water use of recently planted street trees can be determined through quantitative measurements of root ball water loss. Recommendations for an irrigation regime can therefore be developed from knowledge of daily root ball water loss and the amount of water held in the root ball. The recommendation could then be adjusted on-site according to local rainfall. The objective of this study was to develop and test a model that would predict an easily followed irrigation regime for recently planted street trees in Norfolk, VA.

Materials and Methods

An irrigation model was developed and field tested on two street tree species in Norfolk, VA during August and September of 1994. The model was comprised of two primary components. The first was a pan evaporation model for estimation of daily whole tree water loss (10). The second was an estimation of irrigation requirements based on replacement of water predicted to be lost from root balls.

Estimating whole tree water loss in street tree plantings. The Lindsey and Bassuk model estimates daily whole tree water loss through sequential mathematical calculations, presented below:

DAILY TRANSPIRATION = CP x LAI x PE x TR

CP = the **Crown Projection Area (ft^2)** = the ground area beneath the dripline. For a 3-in caliper tree, the average crown diameter is estimated ≈ 8 ft, yielding a CP ≈ 50 ft^2. **LAI** = the approximate **Leaf Area Index** of the tree = the ratio of leaf surface area to CP. Although deciduous trees may have a LAI ranging from 1 to 12, a LAI of 2 is typical for a typical 3-in caliper street tree (10). **PE** = the **Mean Daily Pan Evaporation Rate** = the average daily pan evaporation rate. We used the mean daily pan evaporation rate for the growing season (April - September). In Southeastern Virginia, the 39-year mean monthly pan evaporation rate for the growing season is 6.6 in (13), giving a PE of 0.22 in (0.018 ft). **TR = TRANSPIRATION RATIO** = the ratio of whole tree water loss (transpiration) to pan evaporation. A transpiration ratio of 0.20 was selected (10).

For our study, this model yields an estimated volume of water transpired daily by a 3-in caliper tree during the growing season of 2.7 gallons (103 l) (DAILY TRANSPIRATION = 50 ft^2 X 2 X 0.018 ft X 0.20 =0 .36 ft^3 (2.7 gal)).

Estimating the irrigation requirement. Soil samples were collected from the Norfolk City nursery, within the same nursery rows where the street trees in this project were harvested, and subjected to analysis of physical characteristics (Raleigh Physical Soils Testing Laboratory, Raleigh, N.C.). The soil was a clay loam with an available water holding capacity estimated to be 14% by cross referencing a table developed by Peterson, et al. (11). Additional soil cores were analyzed at the soils laboratory at Virginia

Polytechnic and State University, Blacksburg, VA, to determine moisture loss characteristics at various pressures between 0.03 MPa and 1.5 MPa.

A 3-in (7.5 cm) caliper B&B tree has a 32-in (80 cm) diameter, 21-in (53 cm) depth root ball (1). The amount of water that would be required to wet the root ball to a 20 in depth (1-in allowance for settling during transport) from the permanent wilting point to saturation can then be calculated as R = D x AWHC, (where R = amount of rain or irrigation in inches, D = depth of wetting in inches, and AWHC = available water holding capacity of the soil (volumetric basis)). In this instance, R = 20 in x 0.14=2.80 in (9.7 gal).

The calculated daily whole tree transpiration estimate can be used to determine the length of time the root ball, if wetted to field capacity, could theoretically support the transpiration demands of the tree (9.7 gal (37 l) supply ÷ 2.7 gal (10 l) transpired each day = 3.6 days water supply).

Testing the Model. The irrigation recommendations calculated with the model were tested on two tree species in Norfolk, VA during August and September, 1994. Multiple plantings of 3-in caliper B&B *Pyrus calleryana* 'Redspire' (pear) and *Betula nigra* 'Heritage' (birch) trees planted in an industrial area in March of 1994 constituted the sample population. Planting holes were the same depth and twice the diameter of the root balls, and no soil amendments were added to the backfill. An industrial location was selected because of the unlikelihood that sample trees would be watered by the abutting property owner. The trees were field grown at the Norfolk city nursery. Two treatments were assigned in a completely random design to six replications each of the two species tested (six trees per treatment). Trees assigned to the first treatment (control) were irrigated on an "as-needed" basis, determined by soil moisture sensors. Trees in the second treatment (model) were irrigated so as to replace the predicted water loss. All trees were irrigated by city employees approximately every 14 days throughout May and June. The irrigation schedule followed by the city was a function of available resources rather than actual plant needs. As a consequence, some apparent water stress was visible, although no die back occurred. Irrigation was not required in July as a record 14 in rain was received in Norfolk. Treatments were therefore not applied until August.

To measure soil water status within the root ball, electrical-resistance moisture sensors (Irrometer Company, Inc., Riverside, Calif.) were installed within the root ball on the south side of each tree, 12 in (30 cm) apart, at a depth of six and twelve inches (15 and 30 cm), respectively. Once installed, the wetted moisture sensors required approximately four days to initially dry down to the established irrigation point for the control trees of 0.055 MPa (point recommended for clay soils by moisture sensor manufacturer). An irrigation point of 0.055 MPa, rather than 0.15 MPa (permanent wilting point), was selected so as to maintain the root ball soil moisture above injurious levels. For the model trees, 10 gal (38 l) water was applied to six mulched trees of each species at three day intervals beginning 16 August and continuing through 30 September, 1994. An additional six mulched trees of each species served as controls and were irrigated with 10 gal (38 l) water when either of the two moisture sensors in the root ball reached 0.055 MPa. A rain gauge was also installed at the project location and monitored daily.

Trunk diameters (caliper) were recorded six inches from the top of the root ball in August 1994 and at the conclusion of the experiment in October. In early October, following completion of the irrigation treatments, one representative tree of each species was selected for LAI sampling. Controls, rather than model treatments, were selected because they were irrigated on an "as-needed" basis and would best represent the potential leaf surface area for each species under near optimum soil moisture conditions. Crown projection area was measured and all leaves were hand picked from representative trees and their leaf area measured (LI-3000, LI-COR, Lincoln, Neb.). Irrigation schedules predicted through the model were compared to actual irrigation requirements of controls (those irrigated at 0.055 MPa) to determine how well the irrigation model fit an actual field application. The volume of water applied to model treatments and controls was compared to determine how closely whole tree water use, as predicted through the model, matched the actual water requirements as determined by irrigating when root ball tension reached 0.055 MPa.

Results and Discussion

The 2.8 in (7 cm) water needed every three to four days to maintain root ball moisture within the available range represents a very significant amount of rain. In southeastern Virginia, rainfall events of this magnitude are relatively rare, occurring only during major storms, whereas rainfall events totaling 2 in (5 cm) which would be sufficient to wet the root ball to a 14 in (35 cm) depth (effective rooting area) occur on average every 28 days throughout the growing season (local state climate office). According to our model, almost 22 in (55 cm) rain (77 gal or 29 l) per month would be needed to support each tree during the growing season. The volume calculated through the model would appear to be grossly excessive, particularly since the mean monthly rainfall of 4.3 in (11 cm) received during the growing season seems sufficient to support undisturbed 3-in caliper trees growing in wooded areas. However, unlike their urban, newly-transplanted counterparts, trees in wooded areas typically have unrestricted roots which can exploit a much larger soil water reservoir.

Irrigation regime did not affect caliper during the study period (data not shown). Pear and birch LAI were 2.8 and 1.3, respectively. PE during the experiment (obtained from the nearby state weather station) was similar to historical levels (0.18 in (0.45 cm) vs 0.19 in (0.47 cm)). Recalculation of the model using the slightly lower PE resulted in a change of only 0.2 gal water transpired/day in August.

Substitution of the actual LAI and CP measured for pear and birch controls, 2.8 LAI, 24.1 ft^2 CP and 1.3 LAI, 49.0 ft^2 CP, respectively, into the model equation yields a lower daily transpiration rate (1.8 and 1.7 gal for pear and birch, respectively) for the month of August than originally predicted (2.7 gal based on a LAI of 2.0 and CP of 50 ft^2). For pear, rainfall in Norfolk, VA would therefore, on average, provide only 30 % of the tree's daily water requirements. Actual average daily rainfall in August 1994 was only 0.12 gal (0.46 l), representing approximately 7% of the total daily water requirements for pear. Clearly, rainfall is insufficient to meet transpiration demand without irrigation. Rainfall throughout the experiment, however, was considerably lower than average. Only 2.3 in (6 cm) of rain was received at the project location during August and September in contrast to a 31-year regional average of 9.2 in (23 cm). Due to such variations, our model did not account for rainfall. Homeowners would therefore need to withhold irrigation in periods of heavy rainfall to avoid excessive irrigation.

A total of 130 gal (494 l) of water per tree was applied to each model tree during the experiment while the "as needed" pear and birch control trees required an average of 108 and 122 gal (410 and 464 l) per tree, respectively. Under the conditions of this experiment where natural precipitation was 78% below normal for the month of August, these results indicate that the model closely approximates the actual water requirements of newly planted pear and birch. However, a simple comparison of the total volume of water applied to treatments and controls does not indicate if the 10 gal (38 l) applied at each irrigation was the amount actually transpired or lost from the root ball between water applications. The irrigation volume was based on the amount of water calculated to resaturate the root ball from a soil tension approximating the permanent wilting point (0.15 MPa), but we actually irrigated when soil tension dropped below 0.055 MPa.

To test the accuracy of the predicted water lost through transpiration, the volume of water lost from four soil core samples was determined from 0.03 to 0.1 MPa tension. From these data, volume of water lost per unit volume soil was calculated, and the volume of water loss in the soil core from saturation to 0.055 MPa was determined through linear interpolation. Upon this basis, the amount of water that would be lost in the root ball between saturation and 0.055 MPa was calculated to be 4.6 gal (17 l). The amount of water applied at each irrigation event could therefore theoretically be reduced from 10 to 5 gal (38 to 19 l) per irrigation if soil tension was 0.055 MPa instead of 0.15 MPa. However, 10 gal (38 l) water insures that the root ball will always be saturated at each irrigation, even if the root ball has dried close to the plant wilting point or if some runoff occurs. Although an irrigation threshold of 0.055 MPa soil tension was established for controls, average soil tension recorded in the root ball at the point of irrigation was slightly higher (i.e. the soil was drier), for both species (pear = 0.072 MPa; birch = 0.077 MPa) since root balls dried rapidly at that tension and irrigation at exactly 0.055 MPa was difficult. Irrigation intervals ranged from 2.6 to 3.3 days in pear and from 2.3 to 3.3 days in birch controls. Mean irrigation intervals (2.8 days for pear; 2.9 days for birch) were similar (data not shown). Utilizing the recalculated mean daily transpiration of 1.8 gal (6.8 l) for both species and the mean interval of 2.9 days for control trees, the model predicts whole tree water use between irrigation events of 5.0 gal (19 l) (1.8 gal. daily loss X 2.9 day interval), close to the estimate of 4.6 gal (17 l) from the laboratory analysis. Using the calculated root ball water lost from saturation to 0.055 MPa (4.6 gal or 17 l) and dividing by the newly calculated daily transpiration loss (1.8 gal or (6.8 l), trees should be irrigated every 2.6 days, one day less than the interval predicted with the original assumptions. We rounded the original interval down from 3.6 to 3 days, however.

Although the total water applied between species and treatments were similar, considerably more site visits were required to provide water on an "as-needed" basis. A total of 25 site visits were required to maintain proper soil moisture relations in the pear controls (24 for birch controls) versus 13 for both the pear and birch model treatments. Additionally, the average number of control trees irrigated per visit was higher in birch, indicating a closer match to the model for this species than for pear. The increased number of visits needed to irrigate either species on an "as-needed" basis indicate that irrigation policy based on a predetermined frequency and amount would be more cost effective for city employees to implement, and less confusing for homeowners to follow. In addition, the determination of when trees actually need water is difficult without proper instrumentation.

Conclusions

Because of extreme variability in soil composition and difficulty in conducting controlled research in urban areas, water relations in urban soils and its impact on street tree establishment is not well understood. In this study, the progressive decrease in soil moisture in root balls between irrigation events indicates that water movement from backfill into root balls did not prevent the development of water-limiting conditions. These observations further suggest that root balls, rather than backfill soil, serve as the principal water reservoir during the first growing season. Transpiration estimates calculated through the model also suggest that rainfall is insufficient to meet transpiration demand, indicating a need for irrigation during the first year of establishment to reduce tree water stress.

Our model predicted that newly planted 3-in (7.5 cm) caliper B&B pear and birch should be saturated every three days. The trees used in our study were planted approximately five months before the model was tested. Although casual excavation of a few trees revealed little root growth into the backfill at the beginning of the experiment, some new root growth likely occurred, especially by the end of the experiment. Different results may have been obtained had the model been tested immediately after planting. The saturation of root balls every three days, however, closely approximated actual need during the test period. The estimated volume of 10 gal was excessive, although it assured saturation. In areas where surrounding soil is poorly drained, over saturation may result in root anoxia. The irrigation model tested has direct application to the 24 % of large cities which operate a field nursery (7). Application of the model in other localities, which must purchase trees from commercial growers, would be more difficult because of the model's dependency on root ball soil characteristics.

Water issues have serious implications for municipal reforestation programs. Many cities are periodically under water use restrictions which limit the liberty to irrigate. As a result, affected communities are forced to accept increased mortality rates. This model provides a reasonably simple methodology for quantifying supplemental irrigation requirements of individual trees based on site and biological factors. Equipped with this information, municipal foresters should be able to assess the need for supplemental irrigation and more effectively compete for increasingly scarce and costly water resources. Research is needed to determine the leaf area index and average transpiration rates for common street trees. The accuracy of this irrigation model under different site and soil conditions should be tested.

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Résumé. Les restrictions budgétaires forcent plusieurs villes à compter de plus en plus sur le bénévolat pour l'irrigation des arbres. Avec un modèle de bac d'évaporation déjà connu, nous avons développé une méthode pour prédire les besoins en eau – quantité et fréquence – des arbres de rues et l'avons expérimenté, cinq mois après la plantation, avec des *Pyrus calleryana* 'Redspire' (poirier décoratif) et des *Betula nigra* 'Heritage' (bouleau Heritage) de 7,5 cm de diamètre qui étaient entourés de paillis. Le modèle a déterminé que les mottes devraient être saturées avec 45 litres d'eau à tous les trois jours. Lorsque les arbres expérimentaux ont été testés avec ce modèle, on a constaté comparativement après une période de deux mois que les arbres contrôle, irrigués sur la base de « arrosage seulement lorsque nécessaire » et déterminée au moyen de sondes d'humidité placées dans le sol, ont exigé une moyenne de 480 à 545 litres d'eau chacun alors que les arbres testés avec le modèle de prédiction ont exigé une moyenne de 580 litres d'eau chacun. Cependant, les poiriers et les bouleaux de contrôle ont exigé, respectivement, 25 et 24 visites d'arrosage, alors que les arbres testés avec le modèle ont eu besoin de seulement 13 visites d'arrosage. Réajuster les hypothèses obtenues du modèle avec les données actuelles et ajuster la tension de l'eau dans la motte de façon à ce qu'elle soit irriguée bien au-delà du point de flétrissement permanent donnerait un besoin en eau de 22 litres par cycle de trois jours.

Zussammenfassung. Haushaltskürzungen zwingen viele Städte, bei der Bewässerung von Strassenbäumen auf Die Leistung von Freiwilligen zurückzugreifen. Hier sind wirkungsvolle und leicht zu befolgende Arbeitshinweise erforderlich. Wir benutzten ein flaches Evaporationsmodell, um eine Methode zur Vorherbestimmung des Bewässerungs-bedarfs von Straßenbäumen zu entwickeln. Dieses testeten wir fünf Monaten nach dem Verpflanzen an gemulchten, in Ballen geschlagenen *Pyrus calleryana* 'Redspire' und *Betual nigra* 'Heritage' mit einem Stammumfang von 10-12 cm. Das Modell gab vor, daß die Vurzelballen alle drei Tage mit ca. 40 l zu bewässern seien. Im Test mit den Kontrollbäumen, die über Wurzelballensensoren nach Bedarf gewässert wurden, erforderten die Modell—Bäume über einen Zeitraum von zwei Monaten im ganzen jeder 520 l und die Birnen und Birken in der Kontrolle durchschnittlich 432 und 488 l. Die Kontrollbäume erforderten 25 und 24 Überprüfungen, während die Modell—Bäume nur 13 mal kontrolliert werden mußten. Wenn die Ergebnisse des Modells durch die aktuellen Messungen korrigiert werden und der Punkt, an welchem die Wurzelballen gewässwert werden müssen, oberhalb des permanenten Welkepunkts verschoben wird, ergibt sich alle drei Tage ein Bewässerungsbedarf von 20 l.