Journal of Agricultural Studies
ISSN 2166-0379
2017, Vol. 5, No. 4

Developing A Simple Water Use Model of *Ilex x* ‘Nellie R. Stevens’ from Liners to Four Meter Tall Trees

Richard C. Beeson, Jr. (Corresponding author)

Dept. of Horticultural Sciences, University of Florida Institute of Food and Agricultural Sciences Mid-Florida Research and Education Center 2725 S. Binion Road, Apopka, FL 32703, Tel: 407-814-6172, E-mail: rcbeeson@ufl.edu

Hang Thi Thu Duong

Dept. of Environmental Horticulture, University of Florida Institute of Food and Agricultural Sciences Mid-Florida Research and Education Center 2725 S. Binion Road, Apopka, FL 32703,

Tel: 407-233-5093, E-mail: hang.duong@ufl.edu

Roger J. Kjelgren.

Professor of Environmental Horticulture, University of Florida Institute of Food and Agricultural Sciences Mid-Florida Research and Education Center 2725 S. Binion Road, Apopka, FL 32703, Tel: 407-884-2034, E-mail: rkjelgren@ufl.edu

Received: September 8, 2017 Accepted: September 28, 2017 Published: November 3, 2017

doi:10.5296/jas.v5i4.11820 URL: https://doi.org/10.5296/jas.v5i4.11820

Abstract

To meet minimum spring flows, water management districts in Florida sought to make both agriculture and urban landscapes water efficient, which includes tree farms. *Ilex* spp. (holly) trees are endemic to Central Florida and among the most popular landscape trees for their hardness, bright colors and go-anywhere size. To provide a basis for irrigation allocations both during production and in landscapes, daily actual evapotranspiration (ET_A) for three holly trees were measured with weighing lysimeters over 5.75 years, beginning with rooted cuttings and continuing until trees averaged 4.3 meters in height. Empirical models were derived to calculate ET_A based on crown horizontal projected area or trunk caliper, adjusted daily by changes in evapotranspiration (ETo). Average ET_A to produce these hollies was 20 432 L cumulative over 5.75 years.

Keywords: Ilex spp., irrigation scheduling, irrigation modelling, container production, field production, landscape irrigation

1. Introduction

1.1 Understanding Tree Water Needs

1.1.1 Defining Tree Water Use

Trees planted in urban landscapes often require irrigation during all stages of life: during production in containers or as large specimens (Beeson, 1992; Beeson & Keller, 2003), during root system establishment post-transplanting (Gilman, Black, & Dehgan, 1998), in arid climates (Lindsey & Bassuk, 1991), or during drought once established in humid climates. Landscape tree water management requires reasonable estimates of water demand in order to schedule irrigation amounts and timing to conserve water. Estimation is challenging because tree water demand varies with tree size and shape, developmental stages, nutrition, spacing and shading within species, among species, and with environmental effects on rate of water use (Burger et al., 1987; Fitzpatrick, 1980, 1983; Knox, 1989).

Defining tree water use terms is critical: we define measured tree evapotranspiration in volume units of liters (L) day^{-1} as whole tree water use (ET_A). Further, we define calculated tree transpiration rate in depth units of mm day^{-1} as tree water use rate. Tree water use rate is a derived number calculated from measured ET_A divided by some measure of total area of transpiring leaves (Kjelgren, Beeson, Pittenger, & Montague, 2016). Finally, we define tree water demand as either volume or depth of tree water use estimated from empirically-derived constants or variables because tree water use rate (mm day^{-1}), ET_A (L day^{-1}) and transpiring leaf (m^2) are costly and difficult to measure beyond research studies. Here we have measured ET_A with lysimeters and approximated transpiring leaf as the variable, projected crown area (PCA), to derive a Plant Factor (PF), a constant that links the practical use of tree water demand estimation to the most widely accepted variable in managing plant irrigation, reference (or potential) evapotranspiration (ETo; Allen et al., 2005). ETo integrates the weather factors of solar radiation, wind, ambient humidity, and air temperature which drive evaporative pull on leaves for a hypothetical clipped cool-season turf, allowing standard measure of potential water demand among places and between times (Allen et al., 2005).

1.1.2. Canopy Size and Transpiring Leaf Area

The literature review of Wullschleger et al. (1998) reported ET_A ranging from 10 to 200 L day^{-1}, mostly based on differences in canopy size and transpiring leaf area. Most studies quantified whole tree evapotranspiration for relatively short periods of time, typically much less than a year or often shorter. Ruiter (1987) studied ET_A of *Pinus radiata* (radiata pine) using large drainage lysimeters with volumes of 7 m^3. After three years, trees irrigated throughout the period averaged 3-4 m in height, with daily average ET_A over four weeks of 21 L day^{-1}. Edwards (1986) measured daily ET_A of single trees of four species grown in southern New Zealand for a year. At termination, trees ranged from 3.3 to 5.6 m in height. ET_A exceeded 120 L day^{-1} in summer for *Ecualyputus fastigata*, and was near zero for deciduous species during winter. Beeson (2016) quantified average ET_A of three *Acer rubrum* trees using weighing lysimeters (Beeson, 2011) from small liners to 8 m tall trees over five years in Central Florida. Total average volume of three trees was 29 107 L day^{-1} cumulative over nearly five years. During the summer months of the last year, ET_A peaked at 101 L day^{-1}.

1.2 Literature Review

In an experiment of five species of containerized woody plants, Knox (1989) described the primary factors driving whole tree water use as transpiration rates and size. Further, that pan evapotranspiration, a precursor to ETo, could be used to estimate transpiration rates along with plant size to determine volumetric water demand. In Central Florida Beeson (1993) compared water use rate (mm day^{-1}) of container grown (10.2 L) *Rhododendron sp*. ‘Formosa’ to water demand estimated from the ETo (Penman-Monteith equation) corrected by a Plant Factor. The study noted that poor correlations between estimated demand and measured water use rate may have been improved by more frequent measurements of canopy size to capture size changes during periods of rapid growth. Devitt, Morris, & Neuman (1994), measured ET_A of three woody ornamentals in order to improve water demand estimates of *Prosopis alba Grisebach*, *Chilopsis linearis* (Cav.) Sweet var. linearis and *Quercus virginiana* Mill. in Nevada. They found ET_A of oak was closely correlated to all measured growth parameters, defined as height, diameter, and canopy volume.

St.Clair (1994) postulated that a high degree of precision could be expected when water use was estimated from trunk diameter. Although ET_A was related to trunk diameter, the relationship was nonlinear. Simpson (2000) reported that ET_A in L day^{-1} was related to the cross-sectional sapwood area. However sapwood area depends on tree species and tree age. For *Acer rubrum*, a diffuse-porous species, the correlations between ET_A and trunk cross sectional area was shown to be valid for trees up to 100 years of age (Gebauer, Horna, & Leuschner, 2008). But for a ring porous species, such as *Fraxinus* sp., this is only valid for young trees (Kozlowski & Winget, 1963). *Ilex* sp. are diffuse porous, thus are expected to have a very high correlation between ET_A and trunk cross sectional area, especially with their thin bark. Therefore, cross-sectional sapwood area of *Ilex* sp. should be a very good integrator of all factors impacting tree growth, and so could serve as an accurate predictor of whole tree water use. Most all xylem in young tree stems is recently-produced and sapwood-conducting (Greenridge, 1955; Kramer & Kozlowski, 1979). Consequently, stem cross-sectional area should serve as a useful and easily measured estimate of leaf area, therefore representing whole plant water use. Weighing lysimeters are the most precise tool in measuring whole plant water use, and serve as the basis for developing Plant Factors for use in estimating tree water demand and practical water management in nurseries and landscapes.

Most tree water use studies have been conducted in semi-arid to arid climates; much less so in humid climates. More information on estimating tree water demand, either as a rate or as a volume, can aid managers and policy makers in humid regions, especially in subtropical climates with lengthy dry seasons, for managing water in nursery production and tree-dominated landscapes. Our objective was to use tree water use volumes measured from lysimeters to model evapotranspiration rates with measures of tree size such as projected canopy area and trunk cross sectional areas. Hollies (genus *Ilex*) contain many economically important species, particularly those with an evergreen leaf habit in winter. However, there has been little research on water use of *Ilex* tree species. Findings presented here are daily mean ET_A and growth of three individual *Ilex spp*., beginning from rooted cuttings to 4 m tall trees over nearly six years. The objective of this study was to develop Plant Factors from measured ET_A (volume unit) and ETo. Here we used easily measured tree traits that control transpiration- projected canopy area and trunk cross sectional area, such that whole tree water demand can be estimated for improved water management in nursery production and irrigated landscapes.

2. Materials and Methods

2.1. Experimental Setup

2.1.1 Transplanting

Rooted cutting of holly cultivar (*Ilex spp*. `Nellie R. Stephens`) were obtained late winter 2001 from a nursery in north Central Florida. Five uniform rooted cuttings were transplanted into 26 L containers using a 70% composted pine bark: 30% Florida sedge peat: 10% coarse sand substrate amended with 0.68 kg per m^3 of micronutrients and 2.3 kg per m^3 of dolomite limestone to buffer to a pH of 6.0. In years 2004-2005, NuPeat, composed from one-third composted yard waste, one-third composted and screened hardwood bark and one-third Florida sedge peat, replaced existing sedge peat. These five containers were painted inside with a latex paint mixed with copper (Spin-out, Griffin Corp, Valdosta, GA) and the outside covered with aluminium foil to reduce excess container heating and surface evaporation. These containers were also covered with a shallow convex dome to exclude most rainfall and to reduce evaporation from the container substrate. Each subsequent study year, trees were planted during late winter into sequentially larger containers, with the same substrate, fertilization, and container prep followed. In 2002, trees were transplanted in 95 L container, then in 2003 and 2004, a 361 L container. In 2005 and 2006 trees were progressively moved into 760 L and 1140 L containers. In 2003 an appropriately-sized wire basket (32 – COT, Cherokee Manufacturing Inc., St. Paul, MN) was placed in containers to maintain root ball integrity while lifting trees during replanting into larger containers without causing damage to trunks.

2.1.2 Tree Care

Trees were staked, pruned, and fertilized as needed using controlled release fertilizer (Polygon 19N-4.2P-11.6K, Harrell’s Fertilizer Co. Lakeland, FL). Beginning in mid-to-late winter 2002 and each year thereafter, lower tree canopies were pruned up to 40 cm above the root ball to promote tree structure in accordance with Florida Grades and Standards for Nursery Crops (Florida Department of Agriculture and Consumer Services, 1998).

2.2 Experimental Layout

The first year, five study trees were suspended from a 2 m high tripod lysimeter (Beeson, 2011) which consisted of a basket to hold the container suspended from a load cell (SSM-100, Interface Force Inc., Scottsdale, AZ) underneath the tripod. Load cells were connected to a data logger (CR10X, Campbell Scientific, Inc., Logan, UT) and multiplexer system (AM-416 and AM-32) that collected lysimeter mass every half hour and controlled irrigation (Beeson, 2011). In 2002, the three largest trees were placed singly in large weighting lysimeters (Beeson, 2011) in a row oriented east-west. Each triangular lysimeter basket was suspended from three 341 kg load cells (SSM-750, Interface Force Inc., Scottsdale, AZ) attached to steel pillars at apices. A basket accommodated up to a 1.55 m diameter polyethylene container. Study trees remained in the triangular lysimeters from 2002 through 2006.

Spacing of border trees each spring was representative of nursery production at each stage of growth. In 2001 trees were 0.4 m on center using a square arrangement with 95 border trees handled and transplanted the same as the study trees. Lysimeters were randomly placed within a middle row in the block of four rows of 25 containers. In 2002, 18 border trees were transplanted into containers similar to those of the study trees and placed around each triangular lysimeter study tree to maintain tree canopy cover, which provided an initial canopy density of 50 percent, approximating that of a commercial nursery. In 2003, border trees were reduced to 12 per lysimeter to maintain 50% canopy density. In 2004, the number of border trees around each lysimeter was reduced to six to maintain constant canopy density. In 2005, one border tree was placed in the four cardinal directions around each lysimeter, with one tree between lysimeters within the row.

2.3 Irrigation

In 2001, all trees were irrigated concurrently with a micro-irrigation spray stake (24.2 L hr^{-1}, Roberts Irrigation, San Marcos, CA) as needed at midnight. ET_A from each lysimeter was calculated from daily changes in mass between 6:00 am to 10:00 pm EST (earliest sunrise at the site was 6:29 am with latest sunset at 8:26 pm) to avoid corrections for dew condensation and allow excess irrigation to drain. Irrigation was initiated at midnight if the minimum cumulative ET_A exceeded 544 g, equivalent to 6.2 mm of water over substrate surface. Trees were irrigated to excess at night to ensure complete saturation of the substrate to achieve maximum ET_A each day. Irrigation volume was based on the greatest mass change among the five weighed trees, multiplied by 1.15 to account for irrigation non-uniformity and for increases in plant mass due to growth. Irrigation was applied until the slowest increase in mass gain among the five weighed trees achieved the target mass increase to ensure all trees were at 100% container capacity the following morning. Daily ET_A volumes less than 544 g were retained and added to the following day's ET_A. During rain events, container mass often increased due to accumulation in a container or clinging to foliage, especially near sunset. These increases negated some daily ET_A volumes and occasionally prevented an irrigation event. ET_A consisted mostly of transpiration, although some evaporation likely occurred through the trunk opening in the covers.

From 2002 to 2006, irrigation was governed by the lysimeter tree's ET_A. Beginning in May through early November, irrigation algorithms applied water equivalents of 50% of mass change between 6:00 am and 1:00 pm EST at 1:00 pm. This midday irrigation regime occurred consistently each year. Each night, re-saturation of a substrate was accomplished by applying 125% to 135% of the mass change between 6:00 am and 10:00 pm in three equal sub-volumes at 12:00 am, 1:00 am and 2:00 am EST. Water was applied in excess of 100% ET_A to ensure sufficient resources for maximum ET_A each day. Minimal leaching occurred before the third irrigation cycle. In mid-November irrigation reverted back to applications only at night.

3. Data Collection

3.1 Reference Evapotranspiration

Reference evapotranspiration (ETo) was calculated each day from a Campbell Scientific (Logan, UT) weather station located in a grassy field located 25 m west of lysimeters. The weather station consisted of a pyranometer (Li-200; Li-Cor Inc., Lincoln, NE), a tipping bucket rain gauge (TE525, Texas, Instruments, Dallas, TX), temperature/humidity sensor (CS-215, Campbell Scientific Inc., Logan, UT), a wind sensor (Model 014, Met One Instruments, Grants Pass, OR), and a CR10X data logger that used Application Note 4 (Campbell Scientific Inc.) to calculate ETo with resistance as described by Allen, Jensen, Weight & Burman (1989).

3.2 Growth Measurements

Growth measurements of tree height, branch spread of widest width and width perpendicular, and maximum trunk caliper at 0.15 m and 0.30 m above the substrate were recorded on lysimeter trees every three weeks during each growing season for the first 3 years. Beginning year three, trunk circumference was measured with a metal tape measure. At the beginning of year 4, trunk circumference measurements were initiated at 38 cm above the substrate. Horizontal Projected Canopy Area (PCA, m^2) was calculated by multiplying consistent perpendicular measurements of branch spread, north-south and east-west. Trunk cross sectional area (TSCA, cm^2) was calculated for each of three trunk measurement based on trunk circumference.

3.3 Water Use

Usually ET_A was calculated daily as differences between mass recorded at 6:00 am minus mass recorded at 10:00 pm. When partial midday irrigation was in effect, increases in mass from midday irrigation was calculated by the datalogger and added to the daily sum. However, if rare loss of power or common rain events occurred between 6:00 am and 10:00 pm, actual daily cumulative ET_A was estimated as described by Beeson (2006). For power loss, each tree’s daily ET_A before and after the loss was normalized to water volume per unit ETo (Normalized ETo, L mm^{-1}). This assumed leaf area was constant and normalized values varied minimally over short periods of four to seven days without precipitation. Daily ET_A for each missing day was estimated by multiplying the Normalized ETo volume by the measured ETo for each missing day. When rainfall occurred between 6:00 am and 10:00 pm, half hour mass data was plotted to indicate rainfall events. Periods of decreases in mass were summed to estimate ET_A. This was then vetted by normalizing by ETo, then comparing the rain day normalized ET_A to normalized ET_A of recent rainless days.

4. Data Analysis

Daily volumetric water use and average daily air temperature were plotted over the growing season for each year. Measurements of tree cross sectional areas that control transpiration (PCA and TSCA at three heights, in m^2) were regressed against corresponding Normalized ET_A (ET_A ÷ ETo in liters mm^{-1}) on days trees were measured. PCA and TSCAs were averaged each quarter each year and plotted over growing season throughout 5.75 years. Pooled standard deviation for three trees were calculated for each quarter.

5. Results

5.1. Quantificating ET_A

Holly is a slow growing evergreen tree even under well-irrigated conditions. Trees grew from 0.30 m to 4.27 m tall over 5.75 years with an average increase of 0.70 m in height every year. Leaf habit is evergreen, thus, leaf area was relatively constant or increasing throughout the experiment. Bell-shaped variations in ET_A over a year are therefore more reflective of changes in weather - temperature, sun, humidity, and day length - which drove ETo, rather than changes in leaf accumulation or senescence. These bell shapes had longer tails during winter and early spring when temperatures and solar radiation were not high, covering the approximate first third of each year. As shown in Figure 1a, the height of the bell shapes increased over years due to the leaf area increases throughout the experiment. In an area with high humidity such as Florida, changes in ET_A reflects the flux of temperature rather than that of solar radiation over each year. Figure 1b shows the flux in temperature throughout the experiment.

In the first year, trees grew from 0.3 m to 1.04 m tall, and from 0.30 m to 1.12 m in average canopy spread by the end of December. ET_A gradually increased from early March (around day 100), peaked between August and September, and then gradually declined from October onward. The same trend was observed in each following year. Mean cumulative ET_A from March to December for 2001 was 81.2 L with daily ET_A as 0.30 L day^{-1}.

In the second year, trees initiated bud break in late June, followed by a large leaf flush in August. Tree height increased from 1.04 to 1.80 m and average canopy spread increased from 1.12 m to 2.70 m. Mean cumulative ET_A for the entire year was 601.0 L, with daily ET_A of 1.65 L day^{-1}, as shown in Figure 1a. In year three, initial bud break was mid-March, with full leaf flush occurring earlier than previous years. As Figure 1a shows, ET_A in the third year doubled that from the second year, increasing to 3.28 L day^{-1}, with a mean cumulative ET_A of 1196.1 L. The fourth year leaf flush began in early April and extended into mid-May. Trees grew from 2.37 m to 3.12 m tall and from 3.62 m to 4.94 m in average canopy spread. Daily ET_A, as in previous years again doubled, to 7.38 L day^{-1}. Figure 1a shows mean cumulative ET_A for the fourth year was 2692 L. Bud break and duration appears to have varied from year-to-year. During the fifth year, first bud break began in mid-April, with full leaf flush two weeks later, lasting until late June. Trees growth averaged from 3.12 m to 3.89 m in height and from 4.94 m to 6.12 m in average canopy spread by the end of December. As shown in Figure 1a, daily ET_A for the fifth year again more than doubled that of the fourth year to

16.70 L day^{-1} with a mean cumulative ET_A of 6094.6 L. In the sixth year, tree growth slowed, with height reaching 4.27 m and average canopy spread increasing from 6.12 m to 6.63 m before harvesting in the fall. Daily ET_A was 26.8 L day^{-1}, average cumulative ET_A was 9768 L. Figure 1a shows cumulative mean ET_A measured over 5.75 years of production from 0.30 m tall cuttings to 4.27 m tall trees averaged 20 432 L per tree.

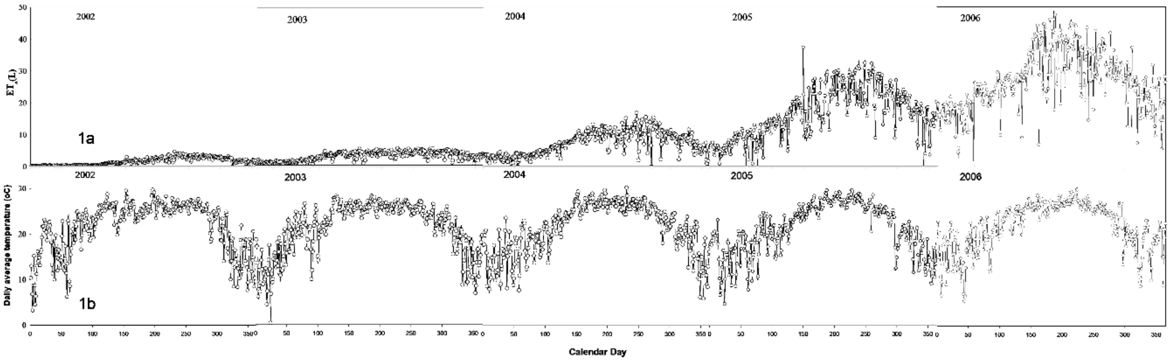

Figure 1. Mean daily ET_A of *Ilex x* `Nellie R. Stephens' (holly) and mean daily temperature in Apopka, Florida from 2001 to 2006

Note. 1a: Each point is based on the mean of three trees replicates, 1b: data obtained from FAWN: Florida Automatic Weather Network

3.2. Modelling daily ET_A

Projected Canopy Area (PCA) and Trunk Cross Sectional Areas (TCSA) were calculated at 0.15 m and 0.3 m, and 0.38 m and, as showing in Figure 2, steadily increased over time. PCA slightly decreased in the first quarter each year because trees were pruned during late February to early March, depending on the year. Thereafter growth quickly recovered.

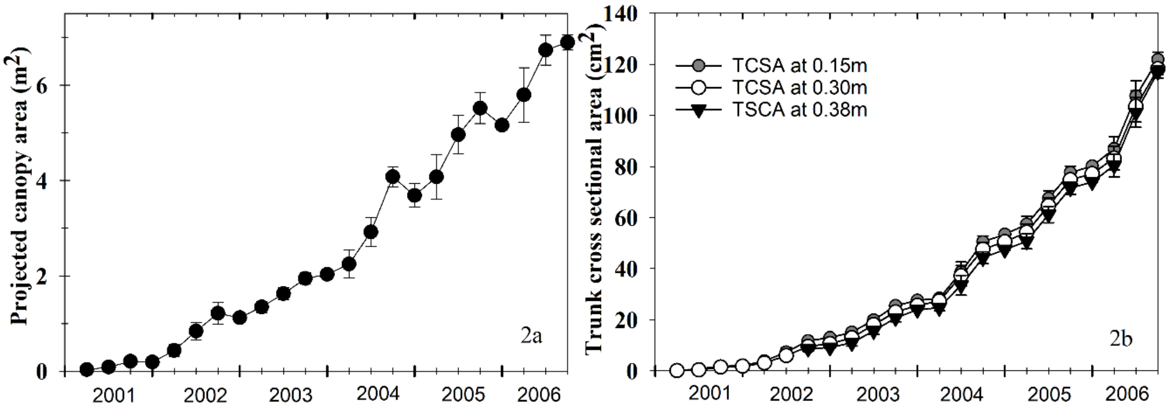

Figure 2: Average quarterly projected canopy area (2a) and trunk cross sectional (2b) for *Ilex x* `Nellie R. Stevens' (holly)

Note: For both 2a and 2b each point is the average of 3 tree replicates; 2b: measured 0.15 m, 0.30 m, and 0.38 m at the first major branch above the soil

Normalized ET_A (N-ET_A; volumetric water use ÷ ETo) was closely and linearly related to the four measures of tree size ($r^2 > = 0.88$ for all four relationships; $P<0.001$; Figure 2). Algebraically rearranging the fitted equation to solve for ET_A yields:

$$Estimated\ ET_A\ (liters) = \frac{ET_o(mm) \times coefficient}{Plant\ factor(slope)\ \times area\ (m^2)}$$

The relationship between N-ET_A and TCSA at all trunk heights was slightly closer and more linear over years than with the measures of PCA at 0.38 m, as shown in Figure 3. Slopes for each equation can be used as coefficients to estimate ET_A (in liters) which can be redefined as water demand for a given duration based on what time period ETo represents, either the previous day or a cumulative number of days.

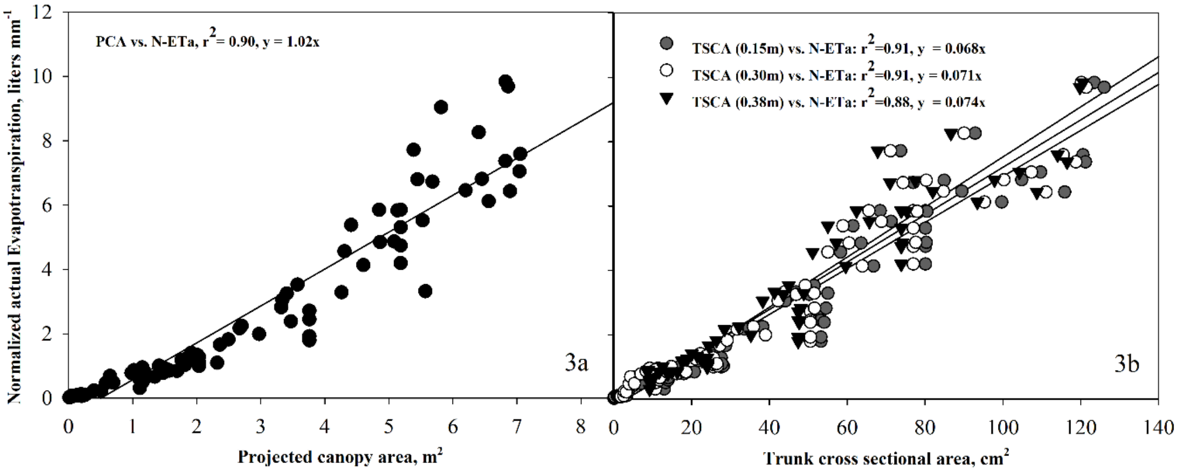

Figure 3: Relationships of Normalized ET_A over 6 years to four measures of horizontal surface areas of *Ilex x* \`Nellie R. Stevens' used to estimate daily ET_A

Note. 3a: Horizontal projected canopy area, 3b: Trunk cross sectional areas at 0.15 m, 0.30 m, and 0.38 m (first major branch) above the soil.

6. Discussion

Tree growth resulted in about 0.7 m of height growth each year. Long growing seasons in Central Florida likely compensated for shorter days (14 hr maximum) and warmer nights compared to northern latitudes. ET_A of the holly trees was maintained quite low for 2-3 months of winter due to relatively low temperatures (20 °C to 25 °C daily Tmax, 10 °C to 15°C Tmin) and low solar radiation which resulted in slow growth of trees. ET_A gradually increased in spring with bud break with warmer temperatures (25 °C to 30 °C daily Tmax, 20 °C to 23 °C Tmin) and longer days, increasing ETo from average 2.6 mm day^{-1} in winter to 5.05 mm day^{-1} in spring, as shown in Figure 1. The bell-shaped pattern of ETo tightly reflects seasonal variability in temperature of the northern hemisphere. The result is in contrast with deciduous maple tree reported by Beeson (2016) that daily ET_A rapidly declined due to shoot growth termination even though ETo remained fairly consistent into September.

Water use of *Ilex sp.* exposes important relationships to environmental conditions that has not been previously reported. Compared to other landscape trees previously reported, ET_A values of holly trees were lower. Pausch, Grote, & Dawson, (2000) reported daily ET_A rates of 61 to 72 L day^{-1} for *Acer saccharum* in forest near Ithaca NY for 24 cm DBH trees. Under similar conditions and experimental setup, Beeson (2016) reported that for red maple trees (*Acer rubrum* L.) in Florida average ET_A to produce trees from 0.4 m to 8 m tall was 29 107 L cumulative over nearly five years, while ET_A for holly trees was 20 461 L per tree over nearly six years since they are not as large.

Correlation between normalized ET_A (ETo/ ET_A) with PCA and TCSA at heights of 0.15 m, 0.30 m, and 0.38 m of the holly trees was high, $r^2>=0.88$, and similar to the relationships between ET_A and the same growth parameters that Beeson (2016) found for red maple. Trunk diameter is closely correlated with tree size and leaf area (Martin, Kloeppel, Schafer, Kimbler, & McNulty, 1998; Simpson, 2000; Vertessy, Benyon, O'Sullivan, & Gribben, 1995) of diffuse-porous trees because tree trunks contain the xylem conduits that supplies transpiring leaf area, and by extension leaf area correlates with water use under a given set of environmental conditions (Beeson, 1997; McDermitt, 1990; Teskey & Sheriff, 1996; Vertessy et al., 1995). For individual species, leaf area and cross-sectional sapwood area are closely related to ET_A in balsam fir (Abies balsamea (L.) *Mill.*) (Coyea & Margolis, 1992), mountain ash (Eucalyptus regnans F.J. Muell.), silver wattle (Acacia dealbata Link.) (Vertessy et al., 1995) and Monterey pine (Pinus radiata D. Don) (Teskey & Sheriff, 1996).

Given the data here, and that leaf area and sapwood area are generally closely related, sapwood area can serve as a predictor of volumetric water demand for individual trees. Either directly as a variable when combined ETo and an appropriate Plant Factor (see Equation 1), or used to estimate PCA, which could then be used in Equation 1. In a study of water use of Interior West Douglas-fir [*Pseudotsuga menzezii* var. glauca (Bessn.) *Franco*] in a natural environment, Simpson (2000) found that for small trees a large portion of basal area (total cross-sectional area of stem at 1.5 m) was sapwood area. Similarly, Sellin (1991) found for a 10-year old dominant Norway spruce [*Picea abies* (L.) Karst.], that approximately 95% of the stem cross-sectional area was conducting sapwood and so contributing to whole plant water use. PCA or TCSA, therefore, can be a relatively good indicator of maximum whole plant potential water use for individual trees when combined with ETo and a Plant Factor appropriate to PCA or TCSA.

A key point of this study is that the slope of the relationship between N-ET_A, which is an estimate of transpiring leaf area after variability from ETo is factored out, and PCA is equivalent to the PF described by Kjelgren et al. (2016). Past tree water use studies often divided ET_A by laboriously harvested total leaf area that may not be the best measure of transpiring leaf area. Total leaf area will include many leaves that are shaded over the course of a day, especially species with dense crowns, so would contribute little to ET_A. PCA is perhaps a less precise measure but is a much simpler and practical way to estimate transpiring leaf area, and with a proper Plant Factor, a much simpler and practical way to estimate volumetric tree water demand.

7. Conclusion

Daily ET_A of *Illex* sp. can be estimated with high precision based on current methods of calculating ETo and using the appropriate coefficients (for PCA or TCSA) for a given measure of tree capacity to move and transpire water, as shown in Figure 3. The three measures using TCSA to estimate water demand (ET_A) are suited to nursery production where trunk diameter (caliper) is a routine measure for marketing classification, but can be used for isolated landscape trees with due consideration. Extrapolations beyond holly sizes measured here are possible and would be most accurate if based on trunk cross sectional area closely below the bottom of first branch, where the greatest reduction of water conducting vessels occurs before transpiration by leaves. *Ilex* sp. are diffuse porous, thus the entire sapwood area is normally conductive to water. Projected canopy area is a more useful approach to estimated whole tree-volumetric water demand not affected by uncertainties in conducting sapwood area in older specimens or ring porous species. The coefficient (slope) for either PCA or TSCA that corrects calculated ETo to holly water use is dimensionless, but to estimate in volume units (either liters or gallons) would require both ETo and PCA/TCSA to be in the same class of units, metric or English.

Acknowledgement

Funding for this project was provided by the Southwest Florida Water Management District and the Horticulture Research Institute.

References

Allen, R. G., Jensen, M. E., Wright, J. L., & Burman, R. D. (1989). Operational estimates of reference evapotranspiration. *Journal of Agronomy*, *81*, 650-662.

Allen, R. G., Walter, I. A., Elliot, R., Howell, T., Itenfisu, D., & Jensen, M. (2005). *The ASCE standardized reference evapotranspiration equation.* Retrieved from the University of Idaho, Kimberly Research and Extension Center, Environmental and Water Resources Institute of the American Society of Civil Engineers website: https://www.kimberly.uidaho.edu/water/asceewri/ascestzdetmain2005.pdf

Beeson, R. C., Jr. (1992). Restricting overhead irrigation to dawn limits growth in container-grown woody ornamentals through small increases in diurnal water stress. *HortScience*, *27*, 996-999.

Beeson, R. C., Jr. (1993). Relationship of potential evapotranspiration and actual evapotranspiration of Rhododendron sp. 'Formosa'. *Proceedings of the Florida State Horticultural Society*, *106*, 274-276. Retrieved from http://fshs.org/proceedings-o/1993-vol-106/274-276%20(BEESON).pdf

Beeson, R. C., Jr. (1997). Using canopy dimensions and potential evapotranspiration to schedule irrigation of *Ligustrum Japonicum*. *Proceedings of the Southern Nursery Association Research Conference*, *42*, 413-416.

Beeson, R. C., Jr. (2006). Relationship of plant growth and actual evapotranspiration to irrigation frequency based on managed allowable deficits for container nursery stock. *Journal of the American Society of Horticultural Science, 131*(1), 140-148.

Beeson, R. C., Jr. (2011). Weighing lysimeter systems for quantifying water use and studies of controlled water stress for crops grown in low bulk density substrates. *Agricultural Water Management*, *98*(6), 967-976. doi: https://doi.org/10.1016/j.agwat.2011.01.005

Beeson, R. C., Jr. (2016). Evapotranspiration and above ground biomass of *Acer rubrum* from liners to 8m tall trees. *American Journal of Plant* Sciences, *7*, 2440-2456.
doi: 10.4236/ajps.2016.717213

Beeson, R. C., Jr., & Keller, K. (2003). Effect of cyclic irrigation on growth of magnolias produced using five in-ground systems. *Journal of Environmental Horticulture*, *21*, 148-152.

Burger, D. W., Hartin, J. S., Hodel, D. R., Lukaszewski, T. A., Tjosvold, S. A., & Wagner, S. A. (1987). Water use in California's ornamental nurseries. *California Agriculture*, *41*, 97-104.

Coyea, M. R. & Margolis, H. A. (1992). Factors affecting the relationship between sapwood area and leaf area of balsam fir. *Canadian Journal of Forest Research, 22*(11), 1684-1693. doi: https://doi.org/10.1139/x92-222

Devitt, D. A., Morris, R. L., & Neuman, D. S. (1994). Evapotranspiration and growth response of three woody ornamental species placed under varying irrigation regimes. *Journal of the American Society for Horticultural Science*, *119*(3), 452-457.

Edwards, W. R. N. (1986). Precision weighing lysimetry for trees, using a simplified tared-balance design. *Tree Physiology*, *1*(2), 127-144.
doi: https://doi.org/10.1093/treephys/1.2.127

Fitzpatrick, G. (1980). Water budget determinations for container-grown ornamental plants. *Proceedings of the Florida State Horticultural Society*, *93*, 166-168. Retrieved from http://fshs.org/proceedings-o/1980-vol-93/166-168%20(FITZPATRICK).pdf

Fitzpatrick, G. (1983). Relative water demand in container-grown ornamental plants. *HortScience*, *18*, 760-762.

Florida Department of Agriculture and Consumer Services (1998). *Grades and Standards for Nursery Plants*. 2nd ed., Tallahassee: *Author.*

Gebauer, T., Horna, V., & Leuschner, C. (2008). Variability in radial sap flux density patterns and sapwood area among seven co-occurring temperate broad-leaved tree species. *Tree Physiology*, *28*(12), 1821-1830. doi: 10.1093/treephys/28.12.1821

Gilman, E.F., Black, R. J., & Dehgan, B. (1998). Irrigation volume and frequency and tree size affect establishment rate. *Journal of Arboriculture*, *24*(1), 1-9.

Greenridge, K. N. H. (1955). Observations on the movement of moisture in large woody stems. *Canadian Journal of Botany*, *33*(2), 202-221. doi: https://doi.org/10.1139/b55-016

Knox, G. W. (1989). Water use and average growth index of five species of container grown woody landscape plants. *Journal of Environmental Horticulture*, *7*(4), 136-139.

Kozlowski, T. T. & Winget, C. H. (1963). Patterns of water movement in forest trees. *Botanical Gazette*, *124*(4), 301-311. Retrieved from http://www.jstor.org/stable/2472915

Kramer, P. J. & Kozlowski, T. T. (1979). *Physiology of Woody Plants*. New York: Academic Press, Inc..

Lindsey, P. & Bassuk, N. (1991). Specifying soil volumes to meet the water needs of mature urban street trees and trees in containers. *Journal of Arboriculture*, *17*(6), 141-149.

McDermitt, D. K. (1990). Sources of error in the estimation of stomatal conductance and transpiration from porometer data. *HortScience*, *25*(12), 1538-1548.

Martin, J. G., Kloeppel, B. D., Schaefer, T. L., Kimbler, D. L., & McNulty, S. G. (1998). Aboveground biomass and nitrogen allocation of ten deciduous southern Appalachian tree species. *Canadian Journal of Forest Research*, *28*, 1648-1659.

Pausch, R. C., Grote, E. E., & Dawson, T. E. (2000). Estimating water use by sugar maple trees: Considerations when using heat-pulse methods in trees with deep functional sapwood. *Tree Physiology*, *20*(4), 217-227.

Ruiter, J. H. (1987). Growth, crop conductance and prediction of stem volume increment of irrigated and non-irrigated young Radiata pine in non-weighing lysimeters. *Forest Ecology and Management*, *20*, 79-96. doi: https://doi.org/10.1016/0378-1127(87)90151-4

Kjelgren, R., Beeson, R. C., Jr., Pittenger, D. R., & Montague, D. T. (2016). Simplified landscape irrigation demand estimation: SLIDE rules. *Applied Engineering in Agriculture*, *32*(4), 363-378. doi:10.13031/aea.32.11307

Sellin, A. (1991). Variation in sapwood thickness of Picea abies in Estonia depending on tree age. *Scandinavian Journal of Forest Research*, *6*, 463-469.
doi: 10.1080/02827589109382683

Simpson, D. G. (2000). Water use of interior Douglas-fir. *Canadian Journal of Forestry Research*, *30*, 534-547.

Schulze, E. D. (1986). Carbon dioxide and water vapor exchange in response to drought in the atmosphere and in the soil. *Annual Review of Plant Physiology*, *37*, 247-274. doi: https://doi.org/10.1146/annurev.pp.37.060186.001335

St.Clair, J. B. (1994). Genetic variation in tree structure and its relation to size in Douglasfir. I. Biomass partitioning, foliage efficiency, stem form, and wood density. *Canadian Journal of Forestry Research*, *24*(6), 1226-1235. doi: https://doi.org/10.1139/x94-161

Teskey, R. O. & Sheriff, D. W. (1996). Water use by Pinus radiata trees in a plantation. *Tree Physiology*, *16*(1_2), 273-279.

Vertessy, R. A., Benyon, R. G., O'Sullivan, S. K., & Gribben, P. R. (1995). Relationships between stem diameter, sapwood area, leaf area and transpiration in a young mountain ash forest. *Tree Physiology*, *15*(9), 559-567.

Wullschleger, S. D., Meinzer, F. C., & Vertessy, R. A. (1998). A review of whole-plant water use studies in trees. *Tree Physiology*, *18*, 499-512.

Copyright Disclaimer