18

Evapotranspiration of Woody Landscape Plants

Richard C. Beeson
University of Florida
USA

1. Introduction

Landscape trees and woody shrubs are important components of residential, commercial and municipal sites, and are nearly ubiquitous in modern non-nomadic societies. Attractive landscaping can increase property values from 6 to 20% in the USA (Hardy et al., 2000; Stigarll & Elam, 2009). Proper selection and placement increases energy efficiency for heating and cooling of structures, provides storm water management, air and noise pollution abatement and carbon sequestration in urban and suburban areas (Dwyer et al., 1992; McPherson et al., 1997; Nowak et al, 2006; Sanders, 1984). An advantage of urban trees is that they are located at the source of highest CO_2 and pollution concentrations, and thus can have the greatest impact, if healthy. McPherson et al. (1999) calculated dollar benefits of the existing urban forest in Modesto, California compared to its annual tree budget cost. Including storm water and air pollution abatement, energy saving and other tangible cost, benefits outweighed cost by 2 to 1. Non-tangible aspects, such as aesthetics, positive psychological being and wildlife habitat are improved when tree and shrub quality are maintained (Hartig et al., 2010; Ulrich, 1986). Healthy maintained landscapes have a calming effect, especially for those who are under stress or depression (Ulrich, 1986).

Though most beneficial in populated areas, urban sites where woody plants are transplanted are often areas not conducive to normal growth. These sites often have constrained soil volumes (Krizek & Dubik, 1987; Lindsey & Bassuk, 1991). This is frequently due to underground utilities or street and building foundations (Ruark et al., 1983). Highly compacted soils are also a major problem (Chi, 1993). If drainage is poor or nonexistent, anaerobic conditions can lead to tree decline and death (Berrang, et al., 1985; Krizek & Dubik, 1987). Conversely, where drainage is acceptable, soil volume and/or plant available water are often inadequate to supply more than a few days of transpirational demands (Lindsey & Bassuk, 1991).

In addition to soil volumes and soil water availability, urban environments are often vastly different from natural woodlands or rural settings. Heilman et al. (1989) planted *Ligustrum japonicum* Thunb. 0.5 m from exterior walls facing the cardinal directions, actual evapotranspiration (ET_A) increased with exposure to sun due to emission of long wave radiation from walls, which increased plant temperature during and after sun exposure. Maximum sap flow was about 30% higher at the west wall than other directions. Whitlow et al. (1992) measured temperature, humidity and solar radiation at street level in a study of urban trees in Manhattan, New York City. They were compared to concurrent measurements a few blocks away in Central Park during the summer for a three year period. Duration of hours of direct sunlight was severely truncated due to shading by tall

buildings at street level. The microclimate within this urban canyon had much higher daily vapor pressure deficits (vpd) than those measured at Central Park (Whitlow et al., 1992). Higher vpd was due to both drier air and higher temperature. Despite high vpd, stomata closure was rare. In a similar study conducted in Seattle, Washington, USA, solar radiation in an urban canyon was restricted to 44% of that received at a nearby park (Kjelgren and Clark, 1992). Like canyon trees in Manhattan, trees maintained an appearance of vigor. This was proposed due to acclimation to generally deep shade, resulting in larger and more leaves. In both studies, trees in the urban canyons rarely exhibited signs of water stress and stomata closure was uncommon. The limited exposure to direct sunlight lowered daily ET_A in both locations to within the volumes of water available to the trees. Additionally, reduced solar radiation would also reduce re-radiated heat from adjacent buildings and pavement. In Seattle, unlike the Manhattan canyon, vpd were similar to those at the park. In contrast, trees growing in a non-shaded paved plaza, a traffic island bordered by three major arteries in Seattle, exhibited symptoms of severe stress, such as small leaves, limited growth and low xylem water potentials. This was proposed due to chronic water stress induced by limited soil volumes and higher evaporative demand. Higher evaporative demand was principally due to two factors, both of which are common, in varying degrees, in all urban and suburban landscapes.

The first factor was wind. In the open area of the plaza surrounded by multilane highways, there were no barriers to impede natural wind. In addition, vehicles travelling at highway speeds would have augmented nature winds and created almost perpetual winds during the majority of a day. Constant winds through isolated trees would have reduced boundary layers of still air around leaves, increasing transpiration. The thinner the boundary layers, the more quickly water molecules are lost to turbulent air around a leaf (Nobel, 2009). Higher wind speeds would have also increased transpiration from shaded interior leaves in the canopy, by both lowering boundary layers and increasing vpd within the canopy by advection of drier air (Rose, 1984) arising from the heated concrete and pavement surrounding the trees.

The other environment factor contributing to severe stress was convection and re-radiation of energy absorbed by the concrete and pavement surrounding these trees. This heat energy absorbed by the leaves would have increased leaf temperature, resulting in increased density of water vapor inside a leaf, leading to a greater gradient of water vapor between inside and outside a leaf. These higher gradients would accelerate transpiration (latent heat loss). To adapt to these two forces, leaf area was substantially reduced to limit heat loading by the surroundings. Smaller leaves also have thinner boundary layers, allowing for greater conduction of heat across the boundary layer.

Whether in urban or rural areas, trees and woody shrubs usually need supplemental irrigation immediately after transplanting into a landscape to speed root growth to re-establish their natural root to leaf ratios. The duration of supplement irrigation depends on plant size and species. In central Florida (lat. 28 N), root growth can occur year round for evergreen species and 10 months for deciduous species. Here root regeneration occurs at a rate of 1 to 5 months per cm in trunk caliper (measured at 15 cm above the soil line; Gilman & Beeson, 1996). For trees with broadly spreading roots, such as *Quercus laurelifolia* and *Pinus elliotii*, establishment was 1 to 1.2 months per cm caliper whether trees were grown in above ground containers or in the ground. Root regeneration was slower for species with dense, slowly expanding root systems, such as *Ilex attenuata* 'East Palatka". Root regeneration for this species was 2.4 month per cm trunk caliper if grown in ground, or 4.8

months if transplanted from a container. Upon analysis of existing literature, Watson (2005) noted that tree establishment after transplanting was generally consistent across hardiness zones if based on trunk caliper and length of growing season when well watered. Under-irrigated trees have sparse canopies. Insufficient leaf area restricts new root generation and elongation. Such trees do not perform their intended functions in a landscape. If they survive, it can take years to regain the vigor and health they had during nursery production. To maintain aesthetically pleasing, healthy plants, supplemental irrigation is frequently required in landscapes after plant establishment. How much water woody plants use, and equally important, how much water they require, is generally unknown. Water use efficiency of most woody plants increases as soil water availability declines, up to a point. Thereafter, excessive stomata closure limits growth and eventually survival. Most research quantifying tree and woody shrub water use has been related to trees under forest conditions, or trees and shrubs during nursery production. Under these conditions, the answers have been to the question of how much water woody plants use. These answers generally establish the highest water use of a species for a given size. These values are ideal for establishing new plants into a landscape or rapidly growing plants to fulfill their place in the landscape. But once this is achieved, continuing to irrigate at production levels can result in excess pruning to maintain plant aesthetics, and is generally wasteful. It is the latter question, how much do plants require that the least is known. Going forward, the discussion will first focus on what is known of how much water plant use. Thereafter the discussion will be of how to modify known plant water use to plant water needs in landscapes and an alternative irrigation strategy that takes advantage of woody plant stomata control and perennial root systems.

2. Woody shrubs

In terms of number of plant species, there has been more research quantifying water use of woody shrubs than quantifying that of trees. However much of this research is based on small plants in 3.8 L containers, with nearly all related to irrigation needs during production. Knox (1989) grew five species of woody shrubs in north Florida (lat. 30.31 N). As plants neared market size, daily water use during late spring to early summer ranged between 0.15 to 0.30 L/day. Burger et al. (1987) grew 22 species of landscape plants in 3.8 L containers at three locations in central (38.33 N) and southern (33.56 N) California. When plants reached marketable size, daily ET_A was quantified by weighing. ET_A was then divided by the container upper surface area and reference evapotranspiration (ETo) at each location to calculate a coefficient (Kc). Actual volumes were not reported, but Kc's were. They ranged from 1.1 to 5.1. Later, Regan (1997) conducted a similar but much larger experiment, calculating Kc for 50 species of woody shrubs and trees in 3.8 L containers in northern Oregon (45.13 N). These Kc's at market size ranged from 2.3 for *Tsuga Canadensis* (l.) Carriere to 5.6 for *Hydrangea macrophylla* Thumb. 'Nikko Blue'. Since container diameters were approximately 15 cm in both studies, if one's local ETo is known, water use for these species could be estimated. However basing Kc on a fixed container diameter is only accurate if plant canopy sizes are similar between the reference plant and the plant ET_A is to be estimated for. Larger plants in the same container would have higher a Kc since larger plants would transpire more water, but the volume would be normalized by the same upper container surface area. Garcia-Navarro et al. (2004) transplanted four plant species from 3.8 L containers into 200 L drainage lysimeters, then allowed them to establish and grow for 15

months in central California (38.33 N). Daily ET_A was then quantified and averaged for three additional months. Mean ET_A was 2.3 L/day for *Spiraea x vanhouttei* (Briot.) Xabel, 1.8 L/day for *Viburnum tinus* L., 1.45 L/day for *Arctostaphylos densiflora* M.S. Baker 'Howard McMinn', and 2.0 L for *Leucophyllum frutescens* (Berl.) I.M. Johnst. Beeson (2001) reported summary results for three woody shrub species averaging marketable size in three container sizes (Table 1; 28.40 N). Mean daily ET_A ranged from 0.255 L for *Rhaphiolepis indica* (L) Lindl. Ex Ker-Gawl grown in 3.8 L containers to 2.53 L for *Viburnum odoratissimum* Ker-Gawl grown in 26.5 L containers. Winter daily water use was generally half the average, while summer water use was 50% more. In 2004, Beeson (2004) presented a graph of daily ET_A of *Ligustrum japonicum* Thumb. grown in 11.4 L containers (28.40 N). At marketable size (0.6 m tall and 0.45 m width) and spaced 43 cm on center, ET_A was about 0.80 L in the spring, with an average ETo of 4.6 mm/day. These ET_A volumes were comparable to flow rates of the same species reported by Heilman and Ham (1990; 30.36 N). Steinberg et al. (1991) reported somewhat smaller daily water use of 0.3 to 0.5 L for market size *Ligustrum japonicum* in. 7.6 L containers in early June in a shaded greenhouse in eastern Texas (30.36 N).

Container size	3.8 L	11.4 L	26.6 L
Species			
Viburnum odoratissimum	0.20 x 0.30 *** 0.40[z]	0.45 x 0.60 *** 1.14	0.90 x 1.2 *** 2.53
Ligustrum japonicum	0.20 x 0.30 *** 0.34	0.45 x 0.60 *** 1.08	0.90 x 1.2 *** 2.36
Rhaphiolepis indica	0.23 x 0.15 *** 0.25	0.57 x 0.38 *** 0.66	0.90 x 0.6 *** 1.48

Mean canopy width (m) x height (m) *** Mean L/day.

Table 1. Mean canopy dimensions and daily water lost (liters) from container grown plants. Means are based on 3 replications per species and container size. Data was collected 1 Jan. 1995 to 31 Dec. 1996 (Beeson 2001).

3. Trees

Most studies of short-term water use of both conifer and hardwood trees have occurred in forest, and thus are not accurately related to water use in landscapes. Yet the same species are among the mainstays of most landscapes. With some adjustment, detailed later, the values derived from forest trees can be used as estimates for trees in landscapes. In 1998 Wullschleger et al. (1998) reviewed forest tree water use reported from 1970 through 1998. The review covered 67 species of trees gleaned from 52 studies. It focused on contributions of the different methods of quantifying tree water use related to a holistic approach for understanding water movement within trees, between canopies and the air above. Ninety percent of the tree water use surveyed ranged from 10 to 200 L/day. Some of the studies included in the review have been included in the discussions here where specific values are relevant to landscape ET_A.

A limited number of studies have quantified water use of small landscape trees. Costello et al. (1996) reported cumulative water loss from three tree species grown in 15.6 L containers in a shaded courtyard versus an open knoll (38.33 N). The daily average over a 14 day period for the open location was 1.2, 1.18 and 0.89 L for *Liquidambar styraciflua* L. *Sequoiadendron giganteum* (lindl.) J. Bucholz and *Magnolia grandiflora* L., respectively. The average reduction in ET_A for trees in the courtyard was 54%. Tree size was not indication. Similar daily ET_A (1.3 L) for a *Taxodium distichum* (L.) Rich growing in a 15.6 L container in

July in Texas (30.36 N) was reported by Steinberg et al. (1990a). In northwest Texas (33.2 N), ET_A of *Prosopis glandulosa* Torr. with trunk diameter of 1.9 cm ranged from 0.25 to 2.5 L per day (Dugas & Mayeux, 1991). Cumulative water use of trees over a full year's growth is seldom reported. However, the annual cumulative ET_A of seedlings of 10 tropical trees transplanted into 200 L drainage lysimeters in India (26.85 N) ranged from 1,358 L for *Pongamia pinnata* (L.) Pierre to 5,324 L for a Eucalyptus hybrid (Chaturvedi et al., 1988).

3.1 Isolated trees

For large to mature trees, daily water use of only a small number of isolated trees have been quantified, and then principally for only a few days to weeks. Montague et al. (2004) measured the ET_A of five species of trees transplanted as balled and burlapped material into in ground weighting lysimeters (41.44 N) during the summer. Mean daily ET_A averaged between 3.2 L/day of *Acer platanoides* L. 'Emerald Queen' (25.2 cm^2 trunk area) to 5.1 L/day for *Fraxinus pennsylvanica* Marsh. 'Patmore' (36.3 cm^2 trunk area). Steinberg et al. (1990b) reported daily ET_A in Texas (32.12 N) of an 11cm caliper *Carya illinoensis* (Wangenh.) K.Koch 'Wichita' during the summer to range from 100 to 150 L per day over a 12 day period in August, based on weighing lysimeter measurements. The tree was 3.9 m tall, with a diameter at breast height (dbh, 1.4 m) of 7.9 cm. Green (1993) reported summer daily water use of a 10 yr old *Juglans* L. species (walnut; 3.4 x 3.1m canopy widths) in New Zealand (40.2 S) to range from 14 to 40 L, depending on environmental factors. In New Zealand pastures (40.08 S), where canopy coverage by *Populus deltoids* (Bart. Ex Marsh, Clone 178) was 66%, ET_A determined by sap flow ranged from 162 to 417 L/day for trees with projected crown areas of 97 to 275 m^2 (Guevara-Escobar et al., 2000). Part of the variability among trees was due to location on the hillside and shading by neighboring trees. Total ET_A was highly correlated with sapwood area (r = 0.86) and dbh (r= 0.93). Ruiter (1987) reported ET_A of Pinus radiata with a caliper of 13 cm (at 15 cm) to average 21 L maximum daily ET_A over a 4 week period (37.49 S) in the summer.

The largest isolated trees measured by lysimetery were reported by Edwards (1986). From these, graphs were published of the daily ET_A of four species of trees, ranging from about 8.9 to 20 cm in caliper at 15 cm (40.21 S). For the deciduous species *Populus x euramericana* (Dode) Guinier cl 'Flevo', with a trunk diameter of about 11 cm, ET_A from fall through early spring ranged from 0 to about 5 L/day. ET_A increased in spring, to maintain between 70 to 90 L/day during summer, dropping quickly to near zero in mid-autumn. A similar seasonal pattern was presented by *Salix matsudana* Koidz. When leafless, ET_A ranged from 0 to 5 L/day. During the peak of summer, ET_A ranged from 50 to 60 L/day for this 8.8 cm trunk diameter tree. An *Eucalyptus fastigata* Dean & Maid 3.3 m tall generally transpired 10 L/day during winter, but increased to a mean of 65 L/day during the summer. The other evergreen species *Pinus radiata* was about 20 cm in caliper. Winter to late spring ET_A was around 40 L/day. Throughout the summer, ET_A ranged from 85 to 125 L/day, decreasing to the 60 to 80 L range in the fall.

3.2 Forest

Within forest, daily tree water use is generally smaller than for isolated trees. In Germany (51.13 N), *Fraxinus excelsior* L. saplings 4.5 m tall and 2.84 cm dbh registered maximum transpirations of about 7 L/day in early August under optimum conditions (Stohr and Losch, 2004). In England (51.27 N), whole tree ET_A was calculated for a *Populus trichocarpa*

Toor. & A.Gray x *P. tacamahaca* L hybrid based on sap flow through branches, scaled to the whole tree level. Trees were growing on a site with a shallow water table. With trunk dbh of 4.2 to 4.6 cm and heights of 5 to 6 m, peak ET_A was 23 to 28 L/day in June (Zhang et al., 1999). In a forest near Melbourne, Australia (37.34 S), the potometer method was used to measure ET_A of a large *Eucalyptus regnans* F.J. Muell. (Vertessy et al., 2007). For a tree 55 m tall and 0.83 m dbh, flow rates through the sapwood ranged from 61 to 323 L/day. Granier (1987) found that dominant trees in a *Pseudotsuga menziesii* Carrière forest (48.44 N) averaged 22 L per day for trees about 18 cm dbh in France during the summer. Schulze et al. (1985) estimated ET_A of a *Picea abies* L. (28 cm dbh; 49.2 N) and a *Larix* hybrid (26 cm dbh; 49.95 N) growing in the Czech Republic and Germany, respectfully. In the summer, ET_A's were 63.1 L the *Picea* and 74.4 L for the *Larix*. More recently Verbeeck et al. (2007) reported maximum daily sap flows of 28 L/day in May for *Pinus sylvestris* L. growing in a forest in the Belgian Campine region (51.18 N). The tree was nearly 20 m tall with a dbh of 26.7 cm.

3.3 Tropical trees

Daily water use of tropical trees is among the highest of species quantified to date. Andrade et al. (1998) measured sap flow of five species of tropical trees in the Panama rainforest (8.58 N) during a period when soil water availability was not limited. Eighteen meter tall *Cecropia longipes* Pitt. with a dbh of 19.7 cm had a cumulative sap flow rate of 46.5 L/day. A *Spondias mombin* L. tree 23 m tall with a dbh of 33.1 cm averaged 80 L/day. *Luchea seemannii* Triana & Planch. was 129 L/day for a 29 m tall tree with a 38.2 cm dbh. A *Ficus insipida* Willd. with a 56.7 cm dbh trunk sap flow rate was 164 L/day for a 30 m tree. The highest sap flow was from an *Anacardium excelsum* (Bertero & Bald. ex Kunth) Skeels tree at 379 L/day from a 15 m tall tree with a 101.8 cm dbh. Total sap flow rate was highly correlated (r=0.99) with trunk dbh.
With the exception of isolated trees in high density urban areas, once trees approach the small forest sizes detailed above, there is little need for supplemental irrigation. On average, if unrestricted, roots systems of landscape trees are generally three times the width of their canopy (Gilman, 1988a, 1988b). At this point, unless there are substantial disruptions to the rooting volume, such as new construction, these large trees in landscapes are self-sufficient in terms of water needs.

3.4 Daily tree water use

While there have been studies quantifying short term water use of landscape trees, or trees that could be used in landscapes, until recently there have been none that track tree water use for the same tree from propagated material (seedlings or rooted cuttings) to trees of landscape stature. In 2001 a project was initiated in Central Florida (latitude 28° 40′) to quantify daily water use of three landscape tree species; *Acer rubrum* L. (red maple), *Quercus virginiana* Mill. (Live oak), and *Ilex x* `Nellie R Stevens' (holly). Both the oak and holly are evergreen species. In early spring 2001 propagules were transplanted in 26 L polyethylene containers and placed in suspension lysimeters (Beeson, 2011). Each tree was surrounded by like trees, but spaced so that canopy coverage was about 50%. Tree ET_A was recorded daily for the following 5 to 6 years as trees were transplanted into ever larger containers up to 1.4 m diameter.

3.4.1 *Ilex*

In six years, the holly tree grew from a trunk caliper of 3.7 mm to 130 mm measured 15 cm above soil line. The holly cultivar, 'Nellie R. Stevens', is slow growing, with an average

maximum height of 9 m (Gilman and Watson, 2006). Like most hollies, it was produced with lower branches left close to the ground. Because this holly was a true evergreen species, after the first two years the tree retained two or three years' worth of leaves. Thus leaf area was relatively constant or increasing throughout the experiment. Bell-shaped variations in ET_A over a year (Fig. 1.B - F) are therefore reflective of changes in ETo than leaf accumulation or senescence. Since ETo is principally driven by solar radiation, the bell-shape pattern reflects seasonal variability in sunlight intensity and duration of the northern hemisphere at the 28˚ latitude. Variability between individual points on all graphs for all species is the day-to-day variation in ET_A. On rare occasions, rainfall was all day or intermittently frequent enough such that there was no discernable mass loss from a lysimeter. These days are indicated by $ET_A = 0$.

In 2001 at the start of the experiment, holly trees averaged 0.3 m tall, with an average canopy width of 12 cm and caliper at 15 cm of a little more than 3 mm (Fig. 1). Average daily ET_A of these rooted cuttings was around 0.15 L. By early fall (Day 255) trees had more than doubled in height to 0.84 m, and increased in average canopy width and caliper 3-fold (0.35 m and 1.25 cm, respectively). Daily water use also increased 3-fold to around 0.5 L/day. During this first year growing period, maximum water use occurred during late summer in July and August. Yet it rarely exceeded 0.55 L/day. By early November (Day 305) tree water use was generally less than 0.4 L/day. Over the course of the 257 days this young tree was measured in 2001, cumulative ET_A was 86 L. Cumulative ETo was 1,074 mm.

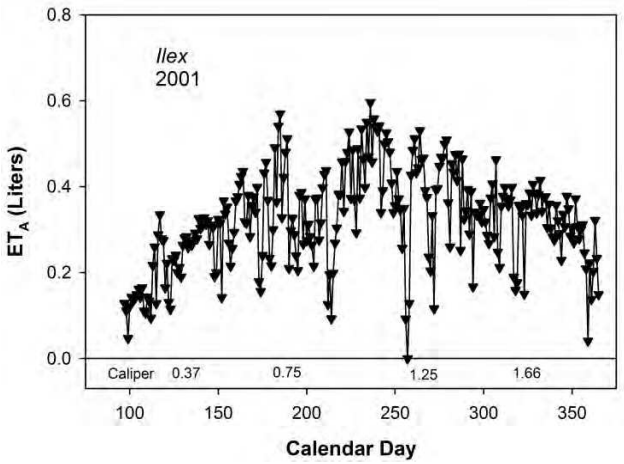


Fig. 1. Mean daily ET_A of the holly, *Ilex* x ' Nellie R. Stevens', for 2001. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

In 2002 mean tree water use remained below 0.4 L per day through mid-March (Day 75, Fig. 2), at the beginning of shoot bud break. During the year tree height increased about 60%, to 2.1 m, with average canopy width doubling to 1.1 m between mid-March and early fall (October, Day 274). However tree water use increased 7-fold from mid-March to early August (Day 213). By mid-November (Day 320), ET_A dropped to about half the value recorded in August, without any loss of leaves, concurrent with a steep decline in daily ETo,

and remained around 2.2 L/day for the remainder of the year. The cumulative ETo for 2002 was 1477 mm, associated with 566 L of cumulative ET_A.

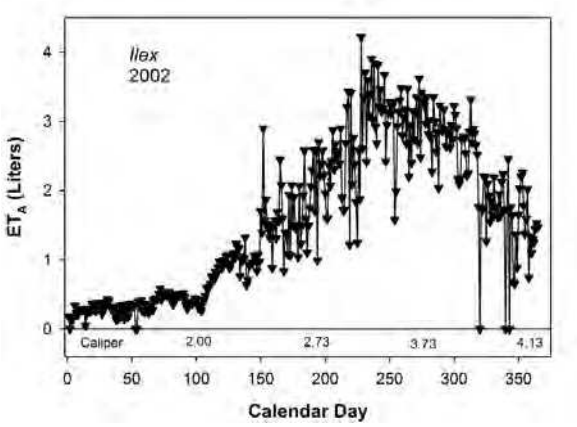


Fig. 2. Mean daily ET_A of the holly, *Ilex* x ' Nellie R. Stevens', for 2002. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

In 2003, cumulative tree water use was 1,305 L that occurred during 1,328 mm of ETo. Increases in daily ET_A slowed to only 40% from the previous year, while tree height increased about 0.6 m for the year to 2.4 m, and canopy width increased to 1.56 m (Fig. 3). This was similar to increases in tree height in 2002 (Fig. 2), but a smaller percent increase in ET_A than the two previous years. From mid-May (Day 135) until December (Day 335) ET_A was generally consistent between 4.7 to 6.2 L/day (Fig. 3). There was little reduction in ET_A in early winter as observed in previous years.

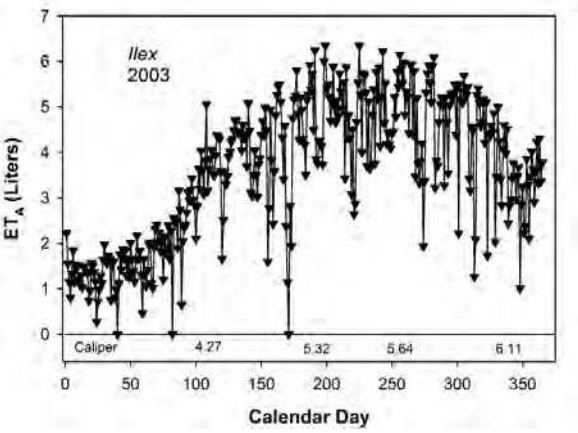


Fig. 3. Mean daily ET_A of the holly, *Ilex* x ' Nellie R. Stevens', for 2003. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

In 2004, ET_A remained at around 4.5 L/day until early April (Day 93, Fig. 4). As in previous years, tree height increased around 0.6 m over the year. Average canopy spread increased to 2.0 m, similar to earlier years. With the increase in canopy spread, tree ET_A increased 3.5 - fold compared to the winter months. Like in previous years, with exception of 2003, ET_A declined by more than half (13 to 6.5 L/day) from early October (Day 275) to early December (Day 336). Although three hurricanes buffeted the research plot in 2004 (Days 220 to 255), they had little effect on ET_A or tree growth the holly. Cumulative ET_A, as trunk caliper increased from 5.9 to 8.0 cm was 2,976 L, with a cumulative ETo of 1,403 mm.

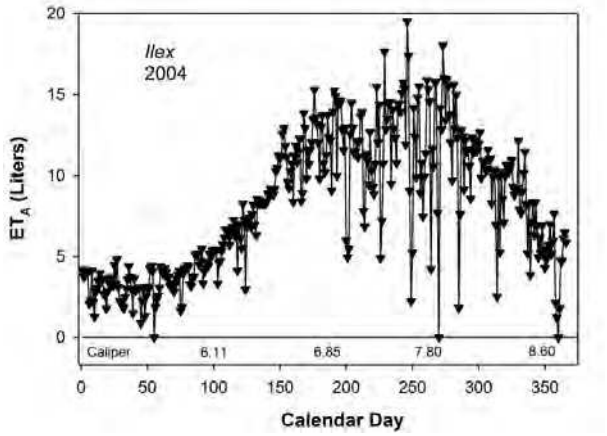


Fig. 4. Mean daily ET_A of the holly, *Ilex* x ' Nellie R. Stevens', for 2004. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

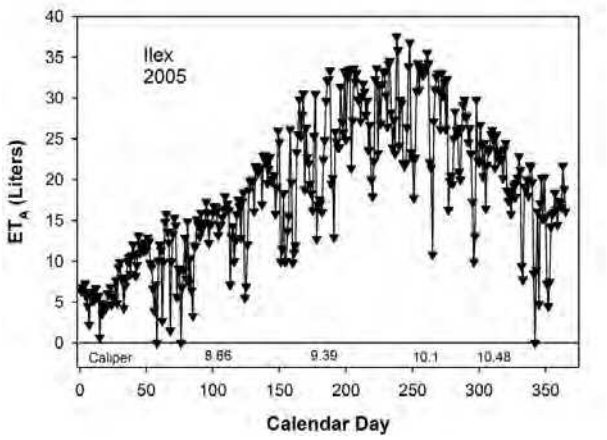


Fig. 5. Mean daily ET_A of the holly, *Ilex* x ' Nellie R. Stevens', for 2005. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

Tree height maintained its constant pace of a 0.6 m increase in 2005. Canopy width increased at a similar constant rate of 0.5 m, while trunk caliper increase was also on pace with previous years at 19 mm. Also consistent was peak ET_A, increasing from 6 to about 34 L/day during summer (Fig. 5). Like previous years, ET_A began declining in early October (Day 275) and was down to about half of its summertime peak by December, corresponding to an approximate halving of daily ETo. Cumulative ET_A for 2005 was 6,789 L with 1,363 mm of ETo.

ET_A in 2006 peaked at around 50 L/day in late June (Fig. 6). At this point the tree was 4.2 m tall with an average canopy width of 2.78 m. From the median ET_A of 17 L/day in January, there was again a 3-fold increase in ET_A from winter to late summer. At its peak, ET_A frequently varied about 50% over periods as short as a week. Similar variability can be seen through all graphs for the holly. In 2006, mean cumulative ET_A was 10,227 L from this tree in a 1.4 m diameter container. Cumulative ETo was 1451 mm. When the experiment was terminated at the end of 2006, total ET_A to grow this tree from a rooted cutting to a tree with a trunk caliper of 13.0 cm, height and width of 4.2 m and 2.8 m, respectively, was 21,949 L.

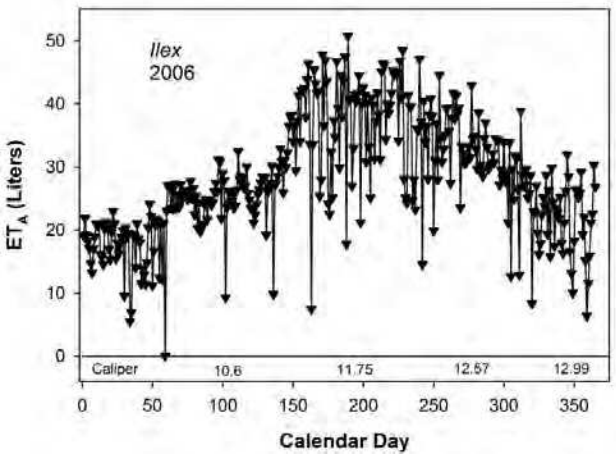


Fig. 6. Mean daily ET_A of the holly, *Ilex* x ' Nellie R. Stevens', for 2006. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

3.4.2 *Quercus*

The Live oak seedling was germinated during the winter of 2000-2001. At the beginning in March 2001, the seedling was 0.38 m tall, with a stem caliper at 15 cm 3.04 mm (Fig. 7). During the first year of growth, tree height increased 3.6-fold, to 1.4 m, with a trunk caliper increase of 4-fold to 1.27 cm. Similar growth rates of Live oak seedlings have been reported before for trees in 11.4 L containers (Beeson and Haydu, 1995). Initial mean ET_A was similar to that of the holly, but ET_A of the oak increased more rapidly, obtaining a 4-fold increase in daily ET_A to 0.76 L/day within 120 days after transplanting (Fig. 7). Unlike holly, ET_A did not decline as much late in the year until late December. Cumulative mean ET_A for 2001 was 136 L.

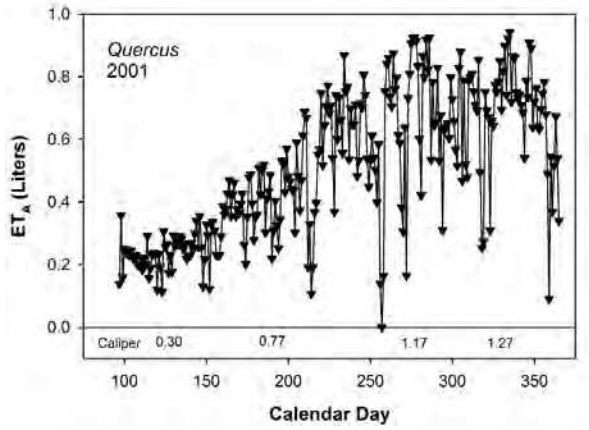


Fig. 7. Mean daily ET_A of the oak, *Quercus virginiana* for 2001. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

Through the first portion of 2002, oak ET_A was around 0.5 L/day until early March (Day 60; Fig. 8). Though not evident in the graph, there was a dip in ET_A from mid-February (Day 45) until early March. This corresponded with annual late winter leaf drop and bud burst of Live oak. With leaf development, ET_A increased relatively gradually from early March through mid-May (Day 140), quadrupling with increasing shoot growth. By mid-August (Day 227), mean daily ET_A had increased to 9.5 L/day with a further increase in early October (Day 275) with a final cycle of shoot flush. In November, tree growth had stopped at 2.63 m in height and increased average canopy width of 2.7 m and trunk caliper of 4.82 cm. By late December, ET_A had declined to 4 L/day, and remained so until bud burst the following spring. Cumulative mean ET_A for 2002 was 1,527 L.

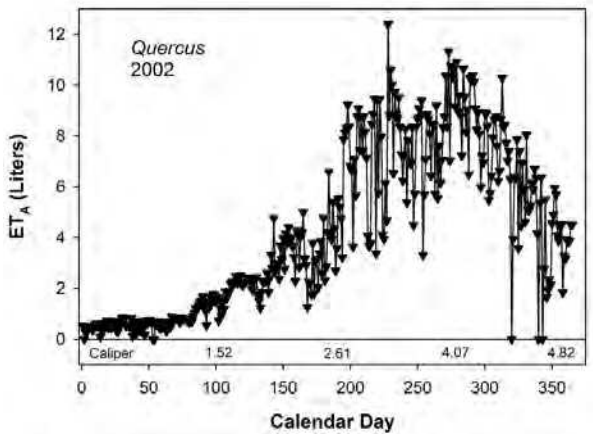


Fig. 8. Mean daily ET_A of the oak, *Quercus virginiana* for 2002. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

In 2003, leaf drop in February briefly reduced daily ET_A to 1 L/day (Fig. 9). ET_A peaked over 36 L/day in mid-September (Day 250) as the tree grew from a height of 2.63 to 3.92 m. Daily ET_A rates between 26 and 30 L/day persisted from early July (Day 182) through mid-November (Day 315), later declining to around 16 L daily by early December. Cumulative mean ET_A for this Live oak in 2003 was 5,728 L. At the end of the year, the tree was 4.12 m tall, with an average canopy width of 2.9 m and trunk diameter of 9.42 cm.

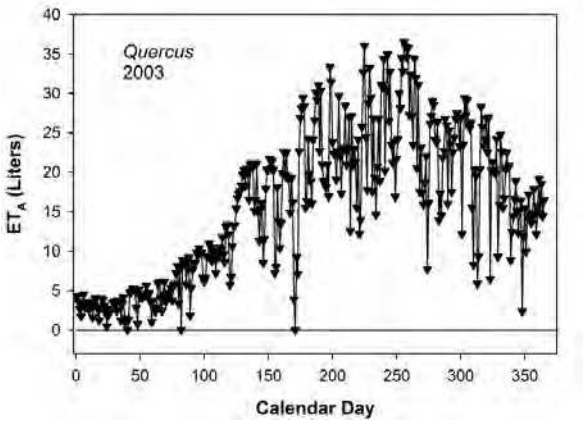


Fig. 9. Mean daily ET_A of the oak, *Quercus virginiana* for 2003. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

In 2004, leaf change occurred closer to mid-March (Day 75), with a substantial decline in ET_A from a few weeks before (Fig. 10). The tree began transpiring at its 2003 peak rates of 30 L/day by early May (Day 125). About 60 days later in early July (Day 185), mean daily ET_A had doubled to over 65 L/day. During this time, tree height had increased by 0.47 m, with mean a mean width increase of 1.0 m. From mid-August (Day 211) through late September (Day 274), the tree was impacted by three hurricanes. The impact was minor with the first two, until the last hurricane, Jeanne, stripped leaves from southeastern side of the tree in late September (Day 273). Peak winds of 145 Km/h were recorded near the site. These leaves were replaced, resulting in a slight bulge in ET_A in late October /early November (Day 290) but with little change in canopy size. By December, ET_A declined to 30 to 35 L/day. Final dimensions of the tree for 2004 were a height of 5.28 m, mean width of 4.0 m and trunk caliper of 13.5 cm. Cumulative ET_A was 12,827 L.

In 2005, the effect of leaf drop on ET_A in the spring was more evident, occurring between late February (Day 50) and late March (Day 80; Fig. 11). By early May (Day 125), ET_A regained its summer peak of 75 L/day the year before. From late June (day 170) to mid-September (Day 255), ET_A was generally around 115 L/day or better. During this time, peak ET_A was 140 L/day with a trunk caliper of 16.7 cm. Tree height increased 0.97 m, while average tree spread increased 0.8 m during 2005. Trunk caliper had the most impressive increase, starting at 14.0 cm in spring and increasing to 16.69 cm by late September. From mid-September (Day 255) to early December, ET_A declined from 130 to 70 L/day with no loss of leaf area, due solely to decreases in ETo from an average of 5.0 mm to 1.6 mm daily. Cumulative ET_A for 2005 was 23,898 L.

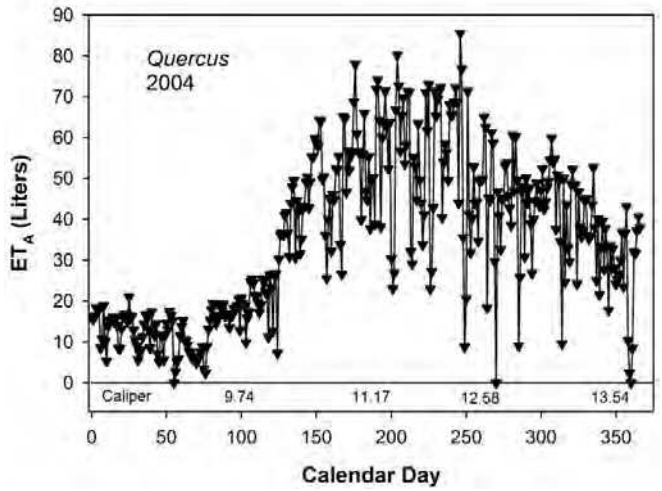


Fig. 10. Mean daily ET_A of the oak, *Quercus virginiana* for 2004. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

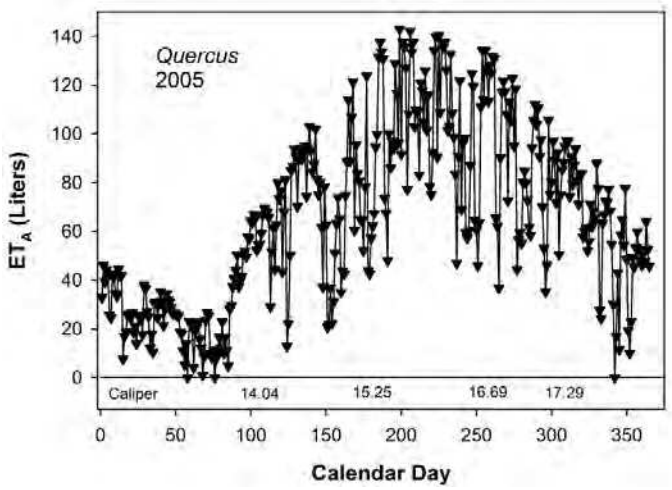


Fig. 11. Mean daily ET_A of the oak, *Quercus virginiana* for 2005. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

In 2006, leaf drop began earlier than in 2005, starting in mid-February (Day 45) and running through early March (Day 70). During this transition, ET_A fluctuated between 30 and 60 L/day. The tree was 6.88 m tall and 5.05 m in average canopy with. Like 2005, trees obtained their previous summer's ET_A in early May (Day 125). Mean ET_A increased to 177 L/ day in

late June. Shortly after the peak, the tree was blown over during a thunderstorm, destroying two of the load cells. Data collection was terminated at this time. Through the duration of data collection, tree height increased from 0.38 to 6.74 m, with a mean canopy width of 5.3 m, a trunk caliper increase from 2.3 mm to 18.73 cm. Until its demise in June, the tree transpired 13,709 L during a period of 689 mm of ETo. Mean cumulative ET_A for this live oak from seedling though mid-June 2006 was 57,825 L.

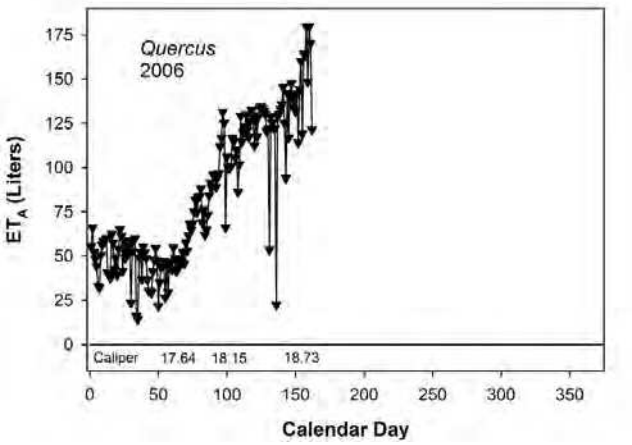


Fig. 12. Mean daily ET_A of the oak, *Quercus virginiana* for 2006. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level. Data collection was terminated early due to storm damage.

3.4.3 *Acer*

Like the holly, the maple was a rooted cutting from a maple selection by Trail Ridge Nursery in north Florida. The maple was the most rapid growing of the species in terms of both shoots and root growth. Each year at transplanting, maples had completely extended their roots throughout the container volume. Being deciduous, fluctuations in ET_A were very dramatic between seasons, like those reported by Edwards (1986). From late December until early March, the tree was leafless. Thus the rise in ET_A in spring was quite rapid. This increase coincided with increasing day lengths and ETo. Conversely, leaf senescence in December lowered ET_A at the same time ETo was declining with shorter days and cooler temperatures. Thus differentiating between changes in leaf area and function, with those related to seasonal changes in ETo are difficult.

In 2001, ET_A of the maple was similar to other species initially, around 0.18 L/day (Fig. 13). As the tree grew from 0.45 to 2.05 m in height the first season, ET_A increased to around 1.1 L/day in mid-August. This ET_A was twice as much as measured for the oak and three times that of the holly. ET_A began declining in mid-September (Day 260) and was quite low by early October (Day 280). This corresponded with a disease on the leaves that induced early leaf senescence. By October, most leaves had fallen. In later years, protective sprays prevented early leaf senescence. When growth ceased for the year, mean canopy width had increased from 0.12 m to 0.65 m, while trunk caliper had increased from 4.9 to 20.0 mm. Cumulative mean ET_A for 2001 was 156 L.

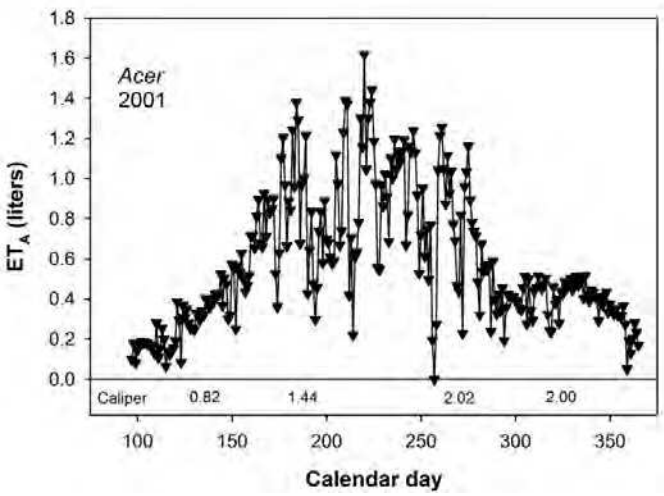


Fig. 13. Mean daily ET_A of the maple, *Acer ruburm* for 2001. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

In 2002 bud break and leaf expansion began in late March, around Day 85 (Fig. 14). Prior to this, ET_A was equivalent to that of the young tree initially, about 0.25 L/day. ET_A increased from near nothing to 3.0 L/day over the next 60 days (Day 140, late May). ET_A was around 11 L/day from late July (Day 205) to early October (Day 275). During this time trees increased from 2.05 to 3.54 m in height and from 0.65 to 1.8 m in canopy spread (Fig. 14). Leaf senescence began in mid-December (Day 350) and was complete by month's end. Cumulative ET_A in 2002 was 1,728 L. Over the year, trunk caliper increased from 2.0 to 5.39 cm.

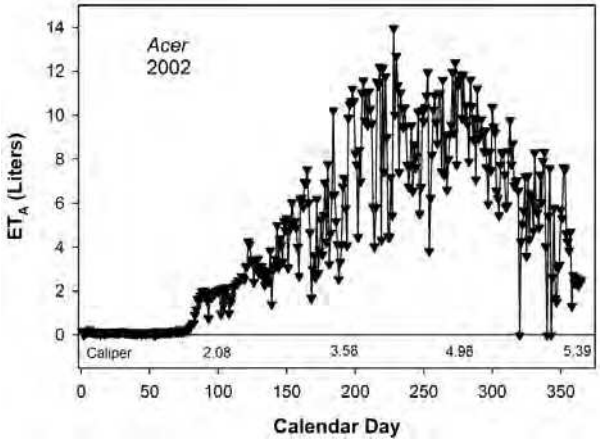


Fig. 14. Mean daily ET_A of the maple, *Acer ruburm* for 2002. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

In 2003, the tree flowered before leaf expansion (Fig. 15). Flowering began in mid-February (Day 45), with leaf and shoot growth not beginning until late March (Day 80). Though there was likely little photosynthesis and no shoot or leaf growth, ET_A more than doubled with flowering, but was still less than 2 L/day. Increase in ET_A was more rapid with the larger tree in 2003 than in 2002 (Fig. 14), with ET_A increasing from 2.0 to 23 L/day in 45 days (Fig. 15). ET_A peaked over 30 L/day in early June (Day 155) and continued generally around 25 L/day through the first week of July. During this period, stems with red leaves, indicative of new and expanding tissue, were 30 to 45 cm in length on most major branches. The second week of July shoot elongation nearly stopped, resulting in a rapid and dramatic drop in expanding leaves. This coupled with maturation of previously expanding leaves resulted in substantial rapid decline in ET_A of 8 L/day. Shoot elongation remained limited thereafter, growing 0.58 m in height, with no measurable increase in average canopy width after the middle of July. Leaf senescence initiated in mid-December and was nearly complete by end of the year. Cumulative ET_A for 2003 was 4,121 L as the tree grew from 3.54 to 5.17 m in height and from 1.56 to 2.9 m in width, with trunk caliper increases of 3.6 cm.

Prior to flower initiation in mid-February 2004 (Day 45), ET_A was less than 4 L/day, and increased to less than 7 L/day during flowering (Fig. 16). With shoot and leaf expansion beginning in mid-March (Day 75), ET_A increased from 7 to 43 L/day over a 45 day period. From early June until mid-July (Day 200), ET_A ranged around 55 L/day. As in 2003, shoot elongation slowed dramatically in mid-July, resulting in ET_A of 38 to 45 L/day until the mid-August leaf loss due to the first hurricane (Charlie) of that year (Day 226). For the remaining of the fall, ET_A dropped following each sequential hurricane as leaves were torn or lost entirely. The 0 ET_A on Day 270 occurred during the peak of Hurricane Jeanne. Thereafter ET_A then steadily declined until leaf senescence was completed in mid-December (Day 350). Despite fall storms, the tree increased in height from 5.17 to 6.9 m and width by 2.9 m to 4.1 m. Cumulative ET_A for 2004 was 9,459 L. Trunk caliper at the end of leaf senescence was 13.25 cm.

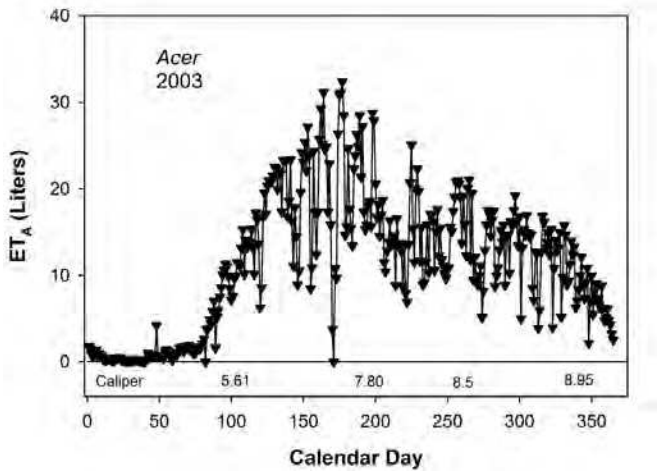


Fig. 15. Mean daily ET_A of the maple, *Acer ruburm* for 2003. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

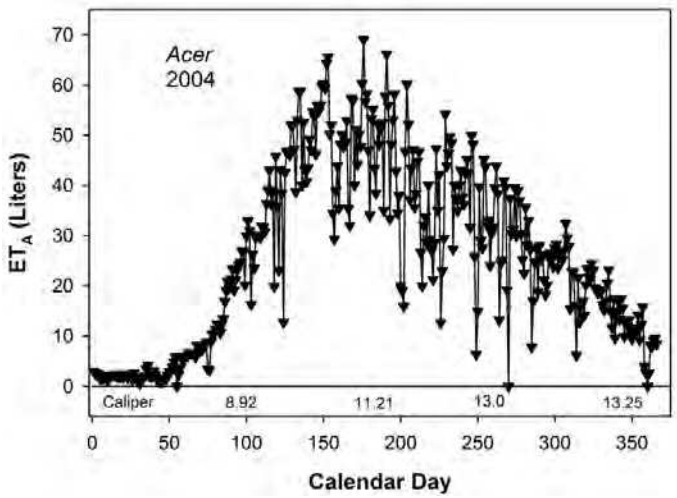


Fig. 16. Mean daily ET_A of the maple, *Acer ruburm* for 2005. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

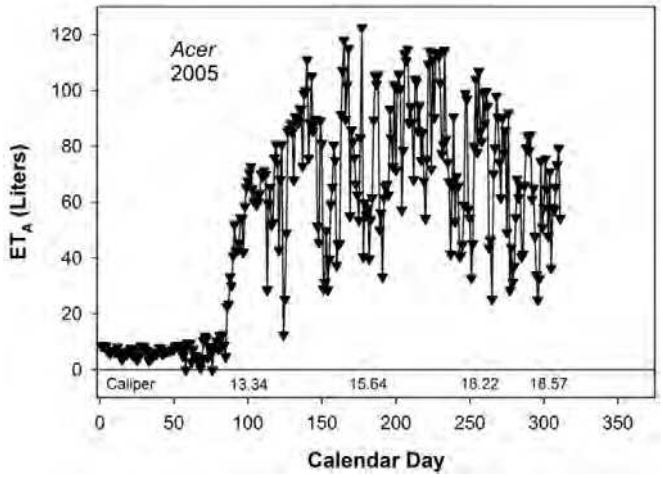


Fig. 17. Mean daily ET_A of the maple, *Acer ruburm* for 2004. Trunk diameter (cm), indicated at the bottom of the graph (Caliper), measured at 15 cm inches above the substrate level.

In 2005, ET_A was around 7 L/day until flowering in mid-February (Day 45, Fig. 17). With onset of shoot elongation (Day 90), tree water use rapidly increased from 11 to 75 L/day over a 2 week period. From first of June (Day 150) until mid-August (Day 225) ET_A was generally around 85 L/day, peaking up to 110 L/day. As in previous years, slowing of shoot elongation reduced ET_A for remainder of the fall, though not as dramatically as in 2003 (Fig. 15). This slowdown in shoot growth occurred about a month later than in previous years. Whether this

was due to being a larger tree with more branches, a residual from stress from hurricanes the year before or a new pattern of grows cannot be determined. Data collection on the maple stopped the first week of November. During this last year, the tree increased 1.1 m in height growth to final height of 8.0 m, and, increased in width by 0.45 m for an average canopy spread of 4.55 m. When terminated, tree caliper was 18.6 cm. Cumulative ET_A for 2005 was 16,491 m during a period when cumulative ETo was 1,242 mm. To grow from a maple of 0.34 m tall to one of 8 m tall required 4.75 years and 31,955 L of ET_A.

4. Translating known ET_A to landscape irrigation

As noted above, ET_A of trees in forest are usually lower than that measured for smaller isolated trees. This effect is due to the degree of canopy closure, measured as projected canopy area (pca) density. In January 2003 (28.48 N), market-quality shrubs of *Viburnum odoratissiumum* in three sizes (3.8, 11.4 and 26.6 L containers) were used to verify a result obtained in 1997 (Beeson, 2010). Mean plant heights were 0.55, 0.80 and 1.23 m for the three container sizes. Plant ET_A was measured at four levels of canopy closure, ~0, 33, 67 and 100% closure with weighting lysimeters (Beeson, 2011) concurrently for nine replications of each container size. The response to canopy closure was identical for each plant size and that observed in 1997 (Fig. 18). Daily ET_A normalized by ETo was the same for isolated plants as those with 33% and 67% canopy closure, i.e. where the cumulative pca's of border and lysimeter plants was 33% and 67% of the total area on which the plants were set. At 100% canopy closure, normalized ET_A declined to 60% of that of plants at 67% closure or less. The ET_A of plants at 100% canopy closure was associated with transpiration from only the upper 40% of a canopy.

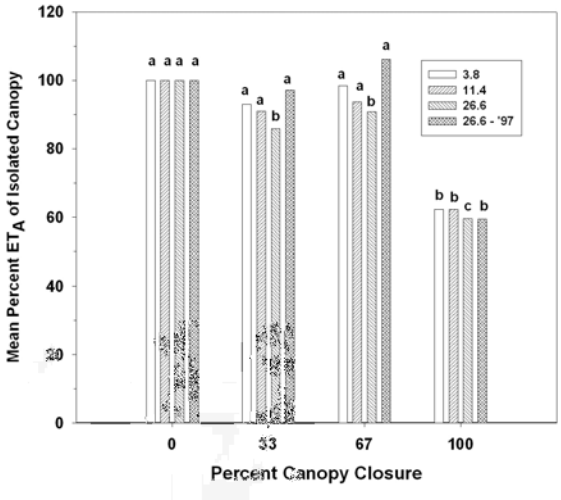


Fig. 18. Normalized ET_A of *Viburnum odoratissimum* of marketable size in three container sizes at four levels of canopy closures. Each bar is the mean of nine plants. Bars with different letters within a container size are significantly different (α=0.5) based on F-Protected LSD.

A complimentary opposite of this effect, increased ET_A, has been reported for trees that remained after forests had been partially harvested to reduce stand density (Bréda et al., 1995; Medhurst et al., 2002). Thus in forested stands, production nurseries and landscape plantings, maximum plant water use will decrease between 70 and 100% canopy closure. This occurs due to mutual leaf shading, increases in leaf boundary layers, and development of canopy boundary layers caused by reductions in canopy roughness. Water use values derived from closed forest or plant production cited above underestimate ET_A in landscapes with less than 70% canopy closure or for isolated trees. Conversely, as landscapes increase in canopy coverage to above 70% canopy closure, water use of the landscape in its entirety will decline.

After accounting for canopy closure, both in examples above and at the location where the information will be applied, utilizing this information is a two stage process. As noted earlier, for optimum establishment, newly transplanted trees and shrubs should be irrigated at their water use rates based on well-watered conditions and size. However once established, research indicates irrigation can be curtailed with woody plants, while still providing their intended aesthetic and functional expectations.

How much irrigation can be reduced has been researched mainly in the western USA. There, research has focused on the minimum level of irrigation that maintains aesthetically pleasing landscapes of established plants. Sachs et al. (1975) limited irrigation frequency of established plants of eight species in central (37.2 N) and southern (33.44 N) California. All species maintained acceptable appearance with only a bimonthly fixed-volume irrigation during the summer dry season. Paine et al. (1992) used a more flexible approach, basing irrigation rates on historical ETo rather than a fixed volume and frequency. They reported acceptable plant appearance of *Photinia fraseri* and *Rhamnus californica* when irrigated at 63.8% of historical ETo, without rain, nine months after transplanting (33.56 N). Pittenger et al. (2001) extended the versatility of using ETo for triggering irrigations (33.56 N), by multiplying daily ETo by a fraction (deficit irrigation level, DI). Irrigation occurred when the cumulative sum exceeded 4 cm, replenishing deep soil moisture. Deficit irrigation levels were 20 to 50% of measured ETo. With typical fluctuations in ETo and winter rainfall with southern California's Mediterranean climate, *Baccharis*, *Drosanthemum*, and *Hedera* irrigated at 20% ETo and *Vinca* at 30% ETo provided acceptable or higher aesthetic quality.

More recently, Shaw and Pittenger (2004) applied their deficit irrigation method on 30 common woody shrub species beginning two years after transplanting (33.56 N). Deficit irrigation treatments were initially 0.36, 0.24 and 0.12 times ETo, but were reduced to 0.36. 0.18 and 0 for the last two years. Aesthetic ratings were the same as used by Pittenger et al. (2001). After three years, 11 of 30 species maintained accept aesthetic quality with no (DI = 0) summer- fall irrigation. Both *Hibiscus* and *Ligustrum* exhibited continuous slow declines suggesting the 0.36 *ETo was insufficient. Three other species were not successful at the 0.36 level, three more (*Cassia*, L*eucophyllum* & *Galvezia*) were unacceptable during the last of summer through winter months. The other 22 species maintained acceptable aesthetical quality at the 0.12 deficit level. These included several shrubs also used in Florida landscapes, which have the opposite climate, i.e. cool dry winters and wet hot summers. These species were *Calliandra*, *Cassia*, *Lantana*, *Leptospermum*, *Otatea*, *Pittosporum tobira*, *Prunus caroliniana*, *Pyracantha* and *Rhaphiolepis indica*.

5. Conclusions

Little research of plant water use to date is directly applicable landscape environments. Most information must be extrapolated from production or ecological research, which often contains insufficient details of plant size or microclimate. Further research with deficit irrigations will increase the list of species that can be successfully infrequently irrigated. However major advances will require quantifying the evaporative demand in urban landscapes and linking that to plant size and algorithms that predict plant water use.

6. References

Andrade, J.L.; Meinzer, F.C.; Goldstein, G.; Holbook, H.M.; Calvelier, J; Jackson, P. & Silvera, K. (1998). Regulation of Water Flux Through Trunks, Branches and Leaves in Trees of a Lowland Tropical Forest. *Oecologia*, Vol.115 pps. 463-471.

Beeson Jr., R.C. & Haydu, J.J. (1995). Economic Feasibility of Micro-Irrigating Container-Grown Landscape Plants. *Journal of Environmental Horticulture,* Vol.15, pp. 23-29.

Beeson, Jr., R.C. (2001). Water Use of Marketable-size Shrubs in Containers - A 2-year Average. *Proceeding of the Southern Nurseryman Association Research Conference,* Vol.46, pp. 592-594.

Beeson, Jr., R. C. (2004). Modeling Actual Evapotranspiration of *Ligustrum japonicum* from Rooted Cuttings to Commercially Marketable Plants in 12 Liter Black Polyethylene Containers. *Acta Horticulturae,* Vol.664, pp. 71-77.

Beeson, Jr., R.C. (2010). Response of Evapotranspiration of *Viburnum odoratissimum* to Canopy Closure and the Implications for Water Conservation during Production and in Landscapes. *HortScience*, Vol.45, pp. 359-364.

Beeson, Jr., R.C. (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,* Vol.98, pp. 967-976.

Bréda, N.; Granier, A. & Aussenac, G. (1995). Effects of Thinning on Soil and Tree Water Relations, Transpiration and Growth in an Oak Forest (*Quercus petraea* (Matt.) Liebl.). *Tree Physiology,* Vol.15, pp. 295-306.

Berrang, P.; Karnosky, D.F. & Stanton, B.J. (1985). Environmental Factors Affecting Tree Health in New York City. *Journal of Arboriculture*, Vol.11, pp. 185-189.

Burger, D.W.; Hartin, J.S.; Hodel, D.R.; Lukaszewski, T.A.; Tjosvoid, S.A. & Wagner, S.A. (1987). Water Use in California's Ornamental Nurseries. *California Agriculture.* Vol.41, No.9/10, pp. 7-8.

Chaturvedi, A.N.; Sharma, S.C. & Srivastava, R. (1988). Water Consumption and Biomass Production of Some Forest Tree Species. *International Tree Crops Journal*, Vol.5, pp. 71-76.

Chi Y.J. (1993). Soil Compaction as a Constraint to Tree Growth in Tropical and Subtropical Urban Habitats. *Environmental Conservation*, Vol.20, pp. 35-49.

Costello, L.R.; Thomas, D. & DeVries, J. (1996). Plant Water Loss in a Shaded Environment: A Pilot Study. *Journal of Arboriculture,* Vol.22, pp. 106-108.

Dugas, W.A.; Heuer. M.L. & Mayeux. H. (1992). Diurnal Measurements of Honey Mesquite Transpiration Using Stem Flow Gauges. *Journal of Range Management*, Vol.45, pp. 99-102.

Dwyer, J.F.; McPherson, E.G.; Schroeder, H.W. & Rowntree, R.A. (1992). Assessing the Benefits and Cost of the Urban Forest. *Journal of Arboriculture*, Vol.18, pp. 227-234.

Edwards, W.R.N. (1986). Precision Weighing Lysimetry for Trees, Using a Simplified Tared-Balance Design. *Tree Physiology* Vol.1, pp. 127-144.

Garcia-Navarro, M.C.; Evans, R.Y. & Montserrat, R.S. (2004). Estimation of Relative Water Use among Ornamental Landscape Species. *Scientica Horticulturae*, Vol.99, pp. 63-174.

Gilman, E.F. (1988a). Predicting Root Spread from Trunk Diameter and Branch Spread. *Journal of Arboriculture,* Vol.14 pp. 85-88.

Gilman, E.F. (1988b). Tree Root Spread in Relation to Branch Dripline and Harvestable Root Ball. *HortScience,* Vol. 23, pp. 351-353.

Gilman, E.F. & Beeson Jr, R.C. (1996). Production Method Affects Tree Establishment in the Landscape *Journal of Environmental Horticulture*, Vol.14, pp. 81-87.

Gilman, E.F. & Watson, D.G. (1993). Ilex x 'Nellie R. Stevens': 'Nellie R. Stevens' Holly. Environmental Horticulture Department, Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida. EDIS EHN472.

Granier, A. (1987). Evaluation of Transpiration in a Douglas-fir Stand by Means of Sap Flow Measurements. *Tree Physiolology,* Vol.3, pp. 309-320.

Green, S.R. (1993). Radiation Balance, Transpiration and Photosynthesis of an Isolated Tree. *Agricultural Forest Meteorology,* Vol.64, pp. 201-221.

Guevara-Escobar, A.; Edwards, W.R.N.; Morton, R.H.; Kemp, P.D. & Mackay, A.D. (2000). Tree Water Use and Rainfall Partitioning in a Mature Popular-Pasture System. *Tree Physiology,* Vol.20, pp. 97-106.

Hardy, J.; Behe, B.K.; Barton, S.S.; Page, T.J.; Schutzki, R.E.; Muzii, K.; Fernandez, R.T.; Haque, M.T.; Booker, J.; Hall, C.R.; Hinson, R.; Knight, P.; McNeil, R.; Rowe, D.B.; & Safley, C (2000). Consumers' Preferences for Plant Size, Type of Plant Material and Design Sophistication in Residential Landscaping. *Journal of Environmental Horticulture*, Vol.18, pp. 224–230.

Hartig, T.; van den Berg, A.E.; Hagerhall, C.M.; Tomalak, M.; Bauer, N.; Hansmann, R.; Ojala, A. ; Syngollitou, E. & Carrus, G. (2010). Health Benefits of Nature Experience: Psychological, Social and Cultural Processes. In *Forest, Trees and Human Health*. (Nilsson, K.; de Vries, S.; Sangster, M.; Seeland, K.; Gallis, C.; Schipperijn, J. & Hartig, T. eds). Springer Science+Business Media B.V. DOI 10.1007/978-90-481-9806-1_5.

Heilman, J.L.; Brittin,C.L. & Zajicek, J.M. (1989). Water Use by Shrubs as Affected by Energy Exchange with Building Walls. *Agricultural and Forest Meteorology,* Vol.48, pp. 345-357.

Heilman, J.L. & Ham, J.M. (1990). Measurement of Mass Flow Rate of Sap in *Ligustrum japonicum*. *HortScience*, Vol.25, pp. 465-467.

Kjelgren, R.; Rupp, L & Kilgren, D. (2000). Water Conservation in Urban Landscapes. *HortScience,* Vol.35, pp. 1037-1040.

Knox, G. W. (1989). Water Use and Average Growth Index of Five Species of Container Grown Woody Landscape Plants. *Journal of Environmental Horticulture*, Vol.7, pp. 136-139.

Krizek, D.T. & Dubik, S.P. (1987). Influence of Water Stress and Restricted Root Volume on Growth and Development of Urban Trees. *Journal of Arboriculture*, Vol,13, pp. 47-55.

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,* Vol.17, pp. 141-149.

McPherson, E.G.; Nowak, D.; Heisler, G.; Grimmond, S.; Souch. C.; Grant, R. & Rowntree, R. (1997). Quantifying Urban Forest Structure, Function, and Value: The Chicago Urban Forest Climate Project. *Urban Ecosystems* 1: 49-61.

McPherson, E.G.; Simpson, J.R.; Peper, P.J. & Xiao, Q. (1999). Benefit-Cost Analysis of Modesto's Municipal Urban Forest. *Journal of Arboriculture,* Vol.25, pp. 235-248.

Medhurst, J.L.; Battaglia, M. & Beadle, C.L. (2002). Measured and Predicted Changes in Tree and Stand Water Use Following High-Intensity Thinning of an 8-year-old *Eucalyptus nitens* Plantation. *Tree Physiology,* Vol.22, pp. 775-784.

Montague, T.; Kjelgren, R.; Allen, R. & Wester, D. (2004). Water Loss Estimates for Five Recently Transplanted Landscape Tree Species in a Semi-Arid Climate *Journal of Environmental Horticulture,* Vol.22, pp. 189-196.

Nobel, P.S. Physiochemical and Environmental Plant Physiology, 4th Ed. (2009). Academic Press. Elsevier Linacre House. Oxford, UK. Pps. 582 ISBN: 978-0-12-374143-1.

Nowak, D. J.; Hoehn III, R.E.; Crane, D.E.; Stevens, J.C. & Walton, J.T. (2006). Assessing Urban Forest Effects and Values, Washington, D.C.'s urban forest. *Resource Bull. NRS-1*. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 24 p.

Paine, T.D.; Hanlon, C.C.; Pittenger, D.R.; Ferrin, D.M. & Malinoski, M.K. (1992). Consequences of Water and Nitrogen Management on Growth and Aesthetic Quality of Drought-Tolerant Woody Landscape Plants. *Journal of Environmental Horticulture*, Vol.10, pp. 94-99.

Pittenger, D.R.; Shaw, D.A.; Hodel, D.R. & Holt, D.B. (2001). Responses of Landscape Groundcovers to Minimum Irrigation. *Journal of Environmental Horticulture,* Vol.19, pp. 78-84.

Regan, R. (1997). Grouping Container-Grown Plants by Water Use. *The Digger*, Vol.41, No.6, pp. 24-27.

Rose, C.W. (1984). Modeling Evapotranspiration: An Approach to Heterogeneous Communities. *Agricultural Water Management,* Vol.8, pp. 203-221.

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,* Vol.20, pp. 79-86.

Ruark, G.; Mader, D.; Veneman, P. & Tatter, T. (1983). Soil Factors Related to Urban Sugar Maple Decline. *Journal of Arboriculture,* Vol.9, pp. 1-4.

Sach, R.M.; Kretchun, T. & Mock, T. (1975). Minimum Irrigation Requirements for Landscape Plants. *Journal of the American Society for Horticultural Science,* Vol.100 pp. 499-502.

Sanders, R.A. (1984). Urban Vegetation Impacts in the Urban Hydrology of Dayton Ohio. *Urban Ecology* 9: 361-376.

Schulze, E.D.; Cremak, J.; Matyssek, R.; Penka, M.; Zimmermann, R.; Vasicck, F.; Gries, W. & Kucera, J. (1985). Canopy Transpiration and Water Fluxes in the Xylem of the Trunk of Larix and Picea trees - A Comparison of Xylem Flow, Porometer and Cuvette Measurements. *Oecologia*, Vol.66, pp. 475-483.

Shaw, D.A. & Pittenger, D.R. (2004). Performance of Landscape Ornamentals Given Irrigation Treatments Based on Reference Evapotranspiration. *Acta Horticulturae,* Vol.664. pp. 607-614.

Steinberg, S.L.; van Bavel, C.H.M. & McFarland, M.J.. (1990a). Improved Sap Flow Gauge for Woody and Herbaceous Plants. *Agronomy Journal,* Vol.82, pp. 851-854.

Steinberg, S.L.; McFarland, M.J. & Worthington, J.W. (1990b). Comparison of Trunk and Branch Sap Flow with Canopy Transpiration in Pecan. *Journal of Experimental Botany,* Vol.41, pp. 654-659.

Steinberg, S.L.; Zajicek, J.M. & McFarland, M.J. (1991). Short-term Effect of Uniconazole on the Water Relations and Growth of *Ligustrum*. *Journal of the American Society for Horticultural Science,* Vol.116, pp. 460-464.

Stigarll, A. & Elam, E. (2009). Impact of Improved Landscape Quality and Tree Cover on the Price of Single-Family Homes. *Journal of Environmental Horticulture*, Vol.27, pp. 24-30.

Stohr, A. & Losch, R. (2004). Xylem Sap Flow and Drought Stress of *Fraxinus excelsior* saplings. *Tree Physiology,* Vol.24, pp. 169-180.

Ulrich, R.S. (1986). Human Responses to Vegetation and Landscapes. *Landscape and Urban Planning,* Vol.13, pp. 29-44.

Verbeeck, H.; Steppe, K.; Nadezhdina, N.; Op De Beeck, M.; Deckmyn,G.; Meirsoone,L; Lemeur, R.; Cermak, J.; Ceulemans, R. & Janssens, I.A. (2007). Stored Water Use and Transpiration in Scots Pine: A Modeling Analysis with ANAFORE. *Tree Physiology,* Vol.27, pp. 1671-1685.

Vertessy, R.A.; Hatton, T.J.; Reece, P.; O'Sullivan, S.K. & Benyon, R.G. (1997). Estimating Stand Water Use of Large Mountain Ash Trees and Validation of the Sap Flow Measurement Technique. *Tree Physiology,* Vol.17, pp. 747-756.

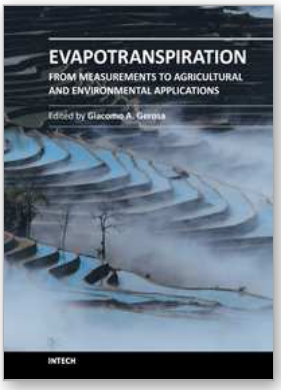
Watson, W.T. (2005). Influence of Tree Size on Transplant Establishment and Growth. *HortTechnology,* Vol.15, pp. 118-122.

Westphal, L.M. (2003). Urban Greening and Social Benefits: A Study of Empowerment Outcomes. *Journal of Arboriculture*. Vol.29, pp. 137-147.

Whitlow, T.H.; Bassuk, N.L. & Reichert, D.L. (1992). A 3-Year Study of Water Relations of Urban Street Trees. *Journal of Applied Ecology*, Vol.29, pp. 436-450.

Wullschleger, S.D.; Meinzer, F.C. & Vertessy, R.A. (1998). A Review of Whole-plant Water Use Studies in Trees. *Tree Physiology*. Vol.18, pp. 499-512.

Zhang, H.; Morison, J.I.L. & Simmonds, L. P. (1999). Transpiration and Water Relations of Poplar Trees Growing Close to the Water. *Tree Physiology*, Vol.19, pp. 563-573.



Evapotranspiration - From Measurements to Agricultural and Environmental Applications
Edited by Dr. Giacomo Gerosa

ISBN 978-953-307-512-9
Hard cover, 410 pages
Publisher InTech
Published online 09, November, 2011
Published in print edition November, 2011

This book represents an overview of the direct measurement techniques of evapotranspiration with related applications to the water use optimization in the agricultural practice and to the ecosystems study. Different measuring techniques at leaf level (porometry), plant-level (sap-flow, lysimetry) and agro-ecosystem level (Surface Renewal, Eddy Covariance, Multi layer BREB), are presented with detailed explanations and examples. For the optimization of the water use in agriculture, detailed measurements on transpiration demands of crops and different cultivars, as well as results of different irrigation schemes and techniques (i.e. subsurface drip) in semi-arid areas for open-field, greenhouse and potted grown plants are presented. Aspects on ET of crops in saline environments, effects of ET on groundwater quality in xeric environments as well as the application of ET to climatic classification are also depicted. The book provides an excellent overview for both, researchers and student,s who intend to address these issues.

How to reference
In order to correctly reference this scholarly work, feel free to copy and paste the following:

Richard C. Beeson (2011). Evapotranspiration of Woody Landscape Plants, Evapotranspiration - From Measurements to Agricultural and Environmental Applications, Dr. Giacomo Gerosa (Ed.), ISBN: 978-953-307-512-9, InTech, Available from: http://www.intechopen.com/books/evapotranspiration-from-measurements-to-agricultural-and-environmental-applications/evapotranspiration-of-woody-landscape-plants

INTECH
open science | open minds

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

© 2011 The Author(s). Licensee IntechOpen. This is an open access article distributed under the terms of the Creative Commons Attribution 3.0 License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.