Evapotranspiration of Urban Landscape Trees and Turfgrass in an Arid Environment: Potential Trade-offs in the Landscape

Tamara Wynne and Dale Devitt

School of Life Sciences, University of Nevada Las Vegas, Las Vegas, NV 89154

Additional index words. evaporation, planting density, transpiration, tree grass water use ratios

Abstract. Irrigation in arid urban landscapes can use significant amounts of water. Water conservation must be based on plant species and the ability to meet plant water requirements while minimizing overirrigation. However, actual evapotranspiration (ET) estimates for landscape trees and turfgrass in arid environments are poorly documented, especially direct comparisons to assess potential trade-offs. We conducted research to quantify ET of 10 common landscape tree species grown in southern Nevada and compared these values with the ET of both a warm season and cool season turfgrass species. The trees were grown in a plot with a high-density planting (256 trees/ha). A complete morphological assessment was made on each tree, and monitoring of plant water status was conducted monthly. ET was quantified with a hydrologic balance approach, irrigating based on the previous week's ET to eliminate a drainage component. Transpiration was estimated with sap-flow sensors, and evaporation was estimated by difference. Although ET in liters revealed no statistical difference based on species, there were many significant differences in tree morphological parameters ($P < 0.05$), such as found with basal canopy area. When ET was converted to centimeters based on standardizing the ET on a basal canopy area basis, statistically higher ET values ($P < 0.05$) were generated for three of the trees (*Lagerstroemia indica*, *Gleditsia tricanthos*, and *Fraxinus velutina* 'Modesto'). A clear separation of all tree ET values (lower ET) with turfgrass ET occurred ($P < 0.001$), with the exception of *L. indica*. Backward regression analysis revealed that all morphological and physiological parameters were eliminated with the exception of percent cover in predicting ET (cm, $R^2 = 0.88$, $P < 0.001$). In addition, a highly curvilinear relationship existed between decreasing percent tree cover and ET on a basal canopy area basis ($R^2 = 0.96$, $P < 0.001$), revealing that smaller trees located within the plot had significantly higher ET (centimeters). Tree-to-grass water use ratios demonstrated that all species except *L. indica* had ratios significantly below 1.0, indicating that on the basis of this study, landscapes dominated by mature trees irrigated at ET would have lower water use rates than similar areas planted to turfgrass, with the exception of the smaller *L. indica*. The results suggest that the smaller trees within the higher planting density plot were partially released from a negative feedback on transpiration that occurred in the larger trees based on reduced canopy atmospheric coupling.

Continued growth in the arid southwestern United States is placing greater demand on available water resources. Much of this growth is in sprawling metropolises where water is used outdoors to support urban landscapes (Devitt et al., 2008; Litvak et al., 2017; St. Hilaire et al., 2008). In the case of the Las Vegas Valley, NV, 60% of the water is used in the residential sector [Southern Nevada Water Authority (SNWA), 2018] and 66% of that is used to irrigate urban landscapes (Devitt et al., 2008). As such, water districts such as SNWA have focused much attention on reducing the outdoor water use component to achieve critical balance between supply and demand.

ET of landscape vegetation varies based on species (size, cover, leaf area index), edaphic and climatic conditions, water quality, and physiological mechanisms that regulate water loss (Devitt et al., 1994; Jarvis and McNaughton, 1986; Nisbet, 2005; Peters et al., 2011; Stevenson, 1989; Wullschleger et al., 2001), however the overall driving force in arid environments is simply how much water is made available to plants (Devitt et al., 1994). In southern Nevada,

annual precipitation is less than 11 cm per year; thus, urban landscapes need significant amounts of irrigation water annually. Although large water savings can always be achieved by deficit irrigating, such an approach should not be implemented on a long-term basis, especially if the irrigation water contains significant levels of soluble salts, as is the case for Colorado River water (EC 1.05 dS·m⁻¹) and reuse water (≈2.00 dS·m⁻¹) used to irrigate landscapes in southern Nevada (Devitt et al., 2007) because it will lead to significant salt accumulation.

Trees play a significant role in urban landscapes by providing beauty, shade, and cooling (McPherson et al., 1989), but they also can consume significant amounts of water (Pataki et al., 2011). In Los Angeles, it is estimated that trees cover more than 13,000 ha, totaling more than 10 million trees (McPherson et al., 2008, 2011) comprising more than 140 species (Nowak et al., 2010), many of which are not native to the region. Although selecting xeric trees for urban landscapes is often recommended in arid environments, Sun et al. (2012) reported that woody species categorized as low water users from xeric habitats actually consumed almost as much water as mesic plants when grown under well-watered conditions.

ET of urban landscape trees have been estimated using various techniques. Closing water balances using lysimeters can be accurate, but these typically have been limited to small trees (Devitt et al., 1994; Levitt et al., 1995), whereas water use of trees growing in a landscape setting have typically been assessed by using sap flow sensors (Litvak et al., 2012; Pataki et al., 2011; Peters et al., 2010) in conjunction with assessments of environmental demand but typically not with a tight water balance that accounts for irrigation, evaporation, and drainage components (Litvak and Pataki, 2016; Pataki et al., 2011). Other techniques such as eddy covariance (Peters et al., 2011) and remote sensing (Nouri et al., 2016) are typically employed over larger scales (urban forest as opposed to the individual tree) but still require field validation to verify accuracy (typically using a soil water balance approach such as that described by Nouri et al., 2013). Unfortunately closing water balances in the field requires estimating drainage, which can be challenging and requires using such techniques as drainage flux meters (Devitt et al., 2018), chloride balance (Devitt, 1989), or large in situ lysimeters (Sun et al., 2012).

ET of turfgrass has been extensively studied over the past 70 years (Bowman and Macauly, 1991; Brown et al., 2004; DaCosta and Huang, 2006; Devitt et al., 1992; Gibeault et al., 1985; Litvak and Pataki, 2016; Penman, 1948; Schiavon et al., 2017; Shearman and Beard, 1973), and although ET of urban landscape trees have been studied over the past 30 years (Devitt et al., 1993, 1994, 1995; Levitt et al., 1995, 2017; Pataki et al., 2011; Sun et al., 2012; Zajicek and Heilman, 1991), few studies have made direct comparisons between landscape trees

Table 1. Tree morphological characteristics; height, trunk diameter, basal canopy area (BCA), canopy volume, leaf area index (LAI), photosynthetically active radiation (PAR) measured above and below the canopy and the leaf area for leaves in the shade and in the sun taken for all 10 species in 2016 in north Las Vegas. Values are means with 1 SD.

Tree species	Ht (m)	Trunk diam (cm)	Sap wood (mm)	BCA (m²)	Canopy volume (m³)	LAI	PAR ratio	Sun leaf (mm²)	Shade leaf (mm²)
Chilopsis linearis	5.97 ± 0.32 d[z]	10.52 ± 5.05 ab	0.81	24.75 ± 6.52 bc	54.86 ± 15.51 c	0.76 ± 0.01 b	1.27 ± 0.17 ab	2.07 ± 0.23 b	2.47 ± 1.42 ab
Fraxinus velutina 'Arizona'	6.95 ± 0.35 e	17.60 ± 3.71 cd	3.92 ± 0.98 b	19.05 ± 0.97 b	59.11 ± 4.83 c	0.76 ± 0.03 b	1.19 ± 0.01 ab	42.75 ± 6.29 e	45.55 ± 10.54 ef
F. velutina 'Modesto'	4.18 ± 0.21 b	13.09 ± 0.80 b	4.10 ± 2.88 b	16.61 ± 2.69 b	27.43 ± 3.11 b	1.21 ± 0.22 c	1.92 ± 0.33 b	34.88 ± 8.55 e	37.9 ± 10.09 e
Gleditsia tricanthos	4.62 ± 0.83 bc	15.50 ± 1.30 c	1.47 ± 0.28 b	17.72 ± 6.69 b	33.70 ± 18.55 bc	1.25 ± 0.38 c	1.20 ± 0.74 a	36.00 ± 14.31 e	32.9 ± 21.51 def
Lagerstroemia indica	3.73 ± 0.45 ab	8.90 ± 0.81 a	2.30 ± 1.89 ab	5.69 ± 0.64 a	3.14 ± 2.44 a	1.22 ± 0.60 bc	1.61 ± 0.61 bc	5.33 ± 0.681 c	6.23 ± 0.81 c
Prosopis alba	5.30 ± 0.11 c	21.40 ± 0.77 d	0.76 ± 0.13 a	22.16 ± 2.27 b	52.71 ± 28.43 bcd	0.59 ± 0.09 a	1.61 ± 0.46 a	12.7 ± 7.14 cd	16.07 ± 8.41 de
Parkinsonia florida	5.77 ± 0.38 cd	17.86 ± 1.62 c	5.27 ± 1.23 b	29.62 ± 4.70 c	93.10 ± 18.49 d	1.25 ± 0.56 bc	2.65 ± 0.68 c	0.67 ± 0.15 a	0.97 ± 0.12 a
Quercus virginana	7.10 ± 0.27 e	22.25 ± 2.02 d	5.75 ± 1.34 b	20.49 ± 6.57 bc	74.53 ± 29.32 cd	1.82 ± 0.43 c	5.24 ± 2.78 bc	6.23 ± 2.70 c	13.33 ± 2.91 d
Ulmus parvifolia	5.57 ± 0.12 c	15.77 ± 0.81 c	1.71 ± 0.51 b	22.85 ± 4.77 bc	60.42 ± 15.25 cd	0.85 ± 0.42 abc	1.99 ± 0.66 ab	2.53 ± 0.23 b	3.00 ± 0.79 b
Vitex agnus-castus	3.37 ± 0.38 a	12.13 ± 1.62 b	1.43 ± 0.75 a	19.67 ± 4.95 b	27.30 ± 13.84 bc	1.15 ± 0.02 c	1.84 ± 0.31 abc	17.20 ± 4.09 d	23.93 ± 7.62 e

[z]Different lowercase lettering associated with these average values indicates significant differences within each column at the $P < 0.05$ level.

and turfgrass with regard to water use (Devitt et al., 1995; Litvak et al., 2014, 2017; Peters et al., 2011).

The objective of this study was to quantify the ET of 10 landscape trees and two turfgrass species using a soil water balance approach to determine tree grass water use ratios and what this might mean in terms of water use trade-offs in the landscape. In addition, we quantified transpiration (T) using sap-flow sensors, allowing us to indirectly estimate evaporation (E) by difference (E = ET – T). The trees were planted in a high-density setting, allowing us to assess the impact high-density planting (individual % tree cover) had on ET (based on basal canopy area) and E.

Methods

The research was conducted at the University of Nevada Las Vegas Center for Urban Water Conservation in North Las Vegas, NV, from May 2016 to July 2018. A stand of 100 landscape trees was used for the study. The trees had been planted 20 years earlier on 5.2 m (north–south) by 6.2 m (east–west) spacings. The planting density was equal to 256 trees/ha. The tree plot contained 10 replicates of mesquite (*Prosopis alba* Grisebach), ash (*Fraxinus velutina* 'Modesto' and *Fraxinus velutina* 'Arizona'), desert willow (*Chilopsis linearis*), oak (*Quercus virginiana*), palo verde (*Parkinsonia florida*), vitex (*Vitex agnus-castus*), locust (*Gleditsia tricanthos*), elm (*Ulmus parvifolia*), and crepe myrtle (*Lagerstroemia indica*). For this study, three trees of each species were selected from the 100-tree plot, avoiding trees located on the perimeter. All of the trees were surrounded with 1.8-m diameter irrigation basins. The 30 trees selected for this study had their irrigation lines capped off such that water was only delivered via a metered hose (TM075; Great Plains Industries, Inc., Wichita, KS). Before the start of the study, a trencher dug 1.2 m down the center of every row in all directions cutting all roots leaving or entering each individual tree plot (few roots were observed).

A large tall fescue (*Festuca arundinacea* var. Monarch) plot containing 20 draining lysimeters was also selected for the study. The lysimeters were installed more than 20 years earlier (Leskys et al., 1999), consisting of large polyvinyl chloride pipes with sealed end caps. At the bottom of the lysimeters, a layer of diatomaceous earth was placed containing two large ceramic cups that were connected to a vacuum system, enabling the collection of drainage water on a regular basis (twice weekly for 30 min). The lysimeters were 0.5 m in diameter and 1.22 m in depth. Three of the existing lysimeters were selected for the study. In an area 100 m northeast of the tall fescue plot, an additional turfgrass plot was planted to bermu-

dagrass (*Cynodon dactylon* var. Tifway) 5 years earlier, and three lysimeters (identical to the tall fescue plot) were selected for the study (Wright et al., 2012). All of the lysimeters were filled with the native North Las Vegas soil attained from the hole dug for the lysimeters, which was leveled to the ground. The soil was classified as a Las Vegas loam (loamy, carbonatic, thermic, shallow Typic Petrocalcids). A weather station was centrally located in the larger fescue plot that monitored atmospheric conditions, enabling estimates of reference evapotranspiration (ET$_{ref}$) using the Penman-Monteith equation (Allen et al., 1998).

Each of the irrigation basins surrounding the 30 trees and all of the lysimeters selected for this study had a single access tube placed to a soil depth of one meter to allow a PR2 Theta Probe (Dynamax, Houston, TX) to be inserted to estimate soil volumetric water content at depths of 10, 20, 30, 40, 60, and 100 cm. Measurements were taken on a weekly basis during the study. These soil moisture estimates were used to quantify the weekly soil water in storage by integrating the soil volumetric water content over the entire soil depth and assigning known soil volumes (depth increment by cross sectional area) to each measurement. Cubic centimeters of water in each depth increment was summed to give weekly soil water in storage estimates. A hydrologic balance was used to estimate evapotranspiration (ET = Input-Output-Change in Soil Water Storage). The input from the equation denotes the irrigation and precipitation that occurred during the previous week. The irrigation to the trees was applied with a hose with a water meter that flowed into a bucket on a mat to prevent the basin from eroding. Grass growing in lysimeters was hand irrigated and temporarily covered during irrigations on the larger plots. The water used in the experiment was groundwater with an EC of 0.40 dS·m⁻¹. The output from the equation denotes the drainage, which was assumed in the tree basins to be negligible based on little or no measured change in soil water content estimates (time domain reflectometry probes) at a depth of 150 cm (one tree of each species). All plants received irrigation water for the next week based on the previous week's ET, thus minimizing the possibility of a drainage component.

Thermal Dissipation Probes (Dynamax) were inserted into the trunks of all experimental trees to continuously measure sap flow. The sensors were all inserted on the north side and at a height of 0.75 m off the ground, surrounded by insulation and reflective foil. The probes selected were 1 cm in length to minimize the insertion of the probe beyond the sapwood that would otherwise distort the measurement. These probes were connected to a data logger in the middle of the stand of trees (CR1000; Campbell Scientific, Logan, UT), recording measurements every 30 s and storing 30-min averages. The data were downloaded to a laptop and analyzed by converting the sap velocity

Table 2. Physiological measurements for all 10 trees in north Las Vegas reported as a mean with 1 SD. $T_c - T_a$ represents the temperature differential between canopy temperature (T_c) and ambient temperature (T_a). Leaf xylem water potential (LXWP) represents average monthly values, whereas stomata conductance refers to readings taken in May 2017.

Tree species	Chlorophyll index	LXWP (MPa)	$T_c - T_a$ (°C)	Stomatal conductance (mmol·m^{-2}·s^{-1})
Chilopsis linearis	170.20 ± 32.07a[z]	−1.79 ± 0.12 a	−1.88 ± 1.05a	131.52 ± 36.88 b
Fraxinus velutina 'Arizona'	172.20 ± 23.95a	−2.18 ± 0.47 ab	−1.42 ± 0.88 a	123.42 ± 19.77 b
F. velutina 'Modesto'	156.93 ± 18.22 a	−2.46 ± 0.67 ab	−2.65 ± 1.32 a	239.34 ± 45.42 c
Gleditsia tricanthos	163.33 ± 37.33 a	−2.44 ± 0.33 b	−1.55 ± 0.81 a	240 ± 43.69 c
Lagerstroemia indica	170.64 ± 21.80 a	−2.19 ± 0.44 ab	−2.70 ± 1.32 a	458.84 ± 144.86 d
Prosopis alba	154.44 ± 28.61 a	−2.66 ± 0.42 b	−1.93 ± 0.74 a	72.3 ± 15.59 a
Parkinsonia florida	136.31 ± 11.67 a	−2.17 ± 0.12 b	−1.10 ± 1.68 a	120.88 ± 69.89 ab
Quercus virginana	165.98 ± 18.32 a	−2.44 ± 0.33 b	−0.84 ± 1.16 a	151.34 ± 158.85 abc
Ulmus parvifolia	150.40 ± 7.29 a	−2.86 ± 0.64 b	−2.97 ± 1.79 a	158.6 ± 25.05 b
Vitex agnus-castus	156.18 ± 17.63 a	−2.56 ± 0.62 b	−3.14 ± 1.32 a	463.18 ± 121.86 d

[z]Different lowercase lettering associated with these average values indicates significant differences within each column at the $P < 0.05$ level.

measurements to transpiration (Granier, 1987). The dimensional parameter K was estimated using K = (ΔTM – ΔT) / ΔT, where ΔT was the difference in temperature between one heated probe and the other non-heated probe. ΔTM is defined as the value of ΔT when there is no sap flow (Granier, 1985, 1987). Sap-flow velocity V (cm/s) is related to K by V = 0.0119 * K$^{1.231}$ (Granier, 1985; Granier et al., 1996). The sap flow of the tree was then determined by the equation $F_s = A_s$* V * 3600 (s/h), where F_s (cm^3/h) is the sap flow, V is the average sap-flow velocity, and A_s is the cross-sectional area of active sapwood (Granier, 1985; Granier et al., 1996). To convert the sap-flow velocities to transpiration, the area of conductive xylem tissue needed to be quantified. The sapwood area was estimated by injecting a colored dye into the conductive tissue as described by Wynne (2019).

Morphological measurements of the trees were taken by an observer who was raised above the tree canopy with a hydraulic lift. Using the lift enabled accurate measurements of height and the canopy rib length in four cardinal directions (start at the top of the canopy and descend down to the base on the outer edge of the canopy). The diameter of the canopy was also measured at the top, middle, and bottom of each tree on a north, south, east, and west basis. Basal canopy area was calculated as an ellipse based on the two diameter measurements taken at the bottom of the canopy. Trunk diameters were measured at a height of one meter. In addition, leaf area index was assessed with a leaf area index wand (LI-COR 2100; LI-COR, Lincoln, NE).

Monthly physiological measurements were taken to verify that the trees were not under water stress based on irrigating at the previous week's ET rate. Physiological measurements were taken at midday (1130 to 1330 HR) on the outer canopy of the trees in direct sunlight at a height of ≈180 cm on fully mature leaves. Canopy temperatures were measured with an infrared thermometer (model 39800; Cole Palmer, Vernon Hills, IL). Leaf xylem water potential was measured with a pressure chamber (PMS Instruments, Albany, OR). Woody stem cuttings were immediately transferred to the pressure chamber where the pressure required to force xylem fluid to reemerge from the cut surface

of the stem was recorded. The pressure was assumed to be equal but opposite the xylem tension (MPa). Chlorophyll index was assessed with a chlorophyll meter based on measuring reflectance at 700 and 840 nm (Field Scout CM1000 Chlorophyll Meter; Spectrum Technologies, Aurora, IL). Stomatal conductance was measured with a porometer with units of mmol·m^{-2}·s^{-1} (SC-1 Porometer; Meter Group, Pullman, WA), but measurements were taken only once during May and June of the second year of monitoring due to equipment failure. Canopy density was assessed by measuring photosynthetic active radiation (*PAR*) (LI-190R; LI-COR) in open areas and comparing that with measurements taken at the base of the canopy of each tree, allowing for a *PAR* ratio (above-to-below) to be generated.

Trees received fertilizer once per year in the early spring (same regimen as the previous 20 years). Nitrogen was applied at a rate of 325 g/tree with a 15–15–15 (N–P–K) fertilizer. Iron chelate was applied at 30 g/tree, and sulfur was applied at 225 g/tree. The grass had ammonium sulfate (21–0–0) fertilizer applied once a month on each lysimeter at a rate of 0.227 kg/92.90 m^2 (0.5 lb of nitrogen per 1000 ft^2). However, in the case of *C. dactyon*, N was not applied from November through March. Clipping height was 5.08 cm for *F. arundinacea* and 2.54 cm for *C. dactylon*. The grass was clipped weekly using hand shears.

Data were analyzed using descriptive statistics, analysis of variance (ANOVA), and linear and multiple regression analysis (Sigmaplot 12.5; Systat Software, San Jose, CA). Backward stepwise regression was performed with deletion of terms occurring when *P* values for the *t* test exceeded 0.05. Multicollinearity was assessed by evaluating variance inflation factors (VIF). If any variable had a VIF value ≥2, the variable was removed, and the data were reanalyzed. The sum total of all VIFs for all variables was not allowed to exceed 10.

Results

Climate. Ambient temperatures measured at a weather station centrally located in the *F. arundinacea* plot ranged from a maximum of 45.3 °C in the summer to a minimum of −3.9 °C in the winter, with a mean tempera-

ture of 26.5 ± 9.6 °C. Rainfall at the site was 93.96 mm for July 2016 through June 2017, and 64.01 mm for July 2017 to June 2018. The mean wind speed was 1.9 ± 0.8 m·s^{-1}. The reference ET (Penman–Monteith) was estimated to be 156.19 cm for July 2016 to June 2017 and 158.32 cm for July 2017 to June 2018.

Morphology of trees. The mature trees ranged in height from 3.73 ± 0.45 m for *L. indica* to 7.10 ± 0.27 m for *Q. virginiana* (Table 1). The maximum average trunk diameter at 1 m from the soil surface was 22.25 ± 2.02 cm for *Q. virginiana* with the smallest average trunk diameter measured at 10.52 ± 5.05 cm for *C. linearis*. The trees had basal canopy areas between 5.7 and 29.6 m^2 (*L. indica* and *P. florida*, respectively). The canopy volume also varied greatly based on species with a maximum of 93.10 m^3 for *P. florida* and a minimum of 3.14 m^3 for *L. indica* and an overall canopy volume average for all species of 48.17 ± 28.38 m^3.

Leaf area index (LAI, Table 1) was lowest for *P. alba* (0.59), which had a very open canopy. *Q. virginiana* exhibited the highest LAI value (1.82). Individual leaf area was assessed for both sun and shade leaves. The smallest individual sun leaf area (leaves located on the outer edge of the canopy) averaged 0.67 mm^2 for *P. florida*. However, some trees had large sun leaves, such as the *G. tricanthos* at 36.00 mm^2 and *F. velutina* 'Arizona' at 42.71 mm^2. Shade leaves (leaves found in the interior of the canopy) ranged in size from 0.97 mm^2 to 45.55 mm^2 for *P. florida* and *F. velutina* 'Arizona', respectively. Only in the case of *Q. virginiana* was there a statistical difference ($P < 0.05$) between sun and shade leaf areas (Table 1), with average shade leaf area being over twice that of the average sun leaf area.

Assessing physiological status of the trees. During the active growing period of each year, we assessed the physiological status of the trees (Table 2) to determine whether irrigation to meet the previous weeks ET led to a systematic decline in plant water status over time. Although there was a certain amount of variation with each parameter, all trees had similar values for the chlorophyll index, and $T_c - T_a$ (canopy minus ambient), with differences being nonsignificant ($P > 0.05$). Only on a few days for a few species
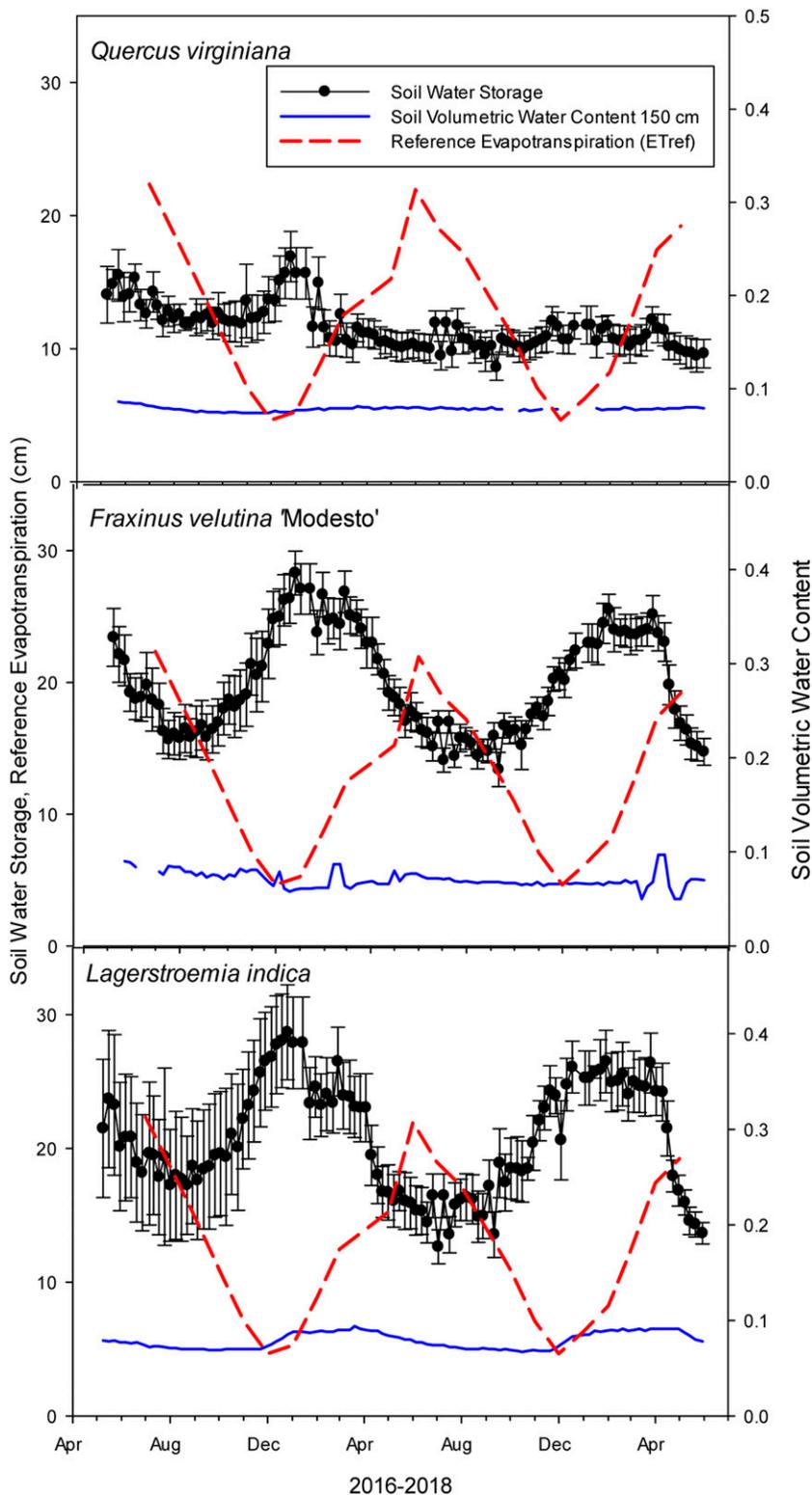
Fig. 1. Soil water storage, reference evapotranspiration (ET$_{ref}$), and soil moisture at 150 cm. All points are means with error bars.

based on the values of ET in the previous week; therefore, when temperatures declined in the fall and ET declined, soil water rose because irrigations were based on the previous week's higher ET. A similar but opposite phenomenon occurred in the spring/summer, when irrigations based on the previous week's lower ET resulted in soil water storage declining.

Closing the water balance required a reasonably accurate estimate of weekly soil water in storage and drainage. We assumed drainage was negligible based on irrigating at ET and the fact that there was little or no change in the soil water content at the 150-cm depth (Fig. 1). *Q. virginiana* was the only species to display a different trend in soil water storage, where it remained mostly unchanged for the entire study period. *Q. virginiana,* was the only species with an evergreen leaf habit, which may explain why the soil water did not fluctuate very much, as the tree remained active year-round.

Evapotranspiration. ET (liters) was estimated with a hydrologic balance approach on each tree, with yearly and 2-year totals reported in Table 3. No statistical difference in ET was observed when ET was reported based simply on liters, possibly the direct influence of the higher planting density. However, the size of the trees (basal canopy area, canopy volume, height) was statistically different. To compare the ET for the 10 tree species, the ET (liters) was standardized with the basal canopy area to generate ET in centimeters. We chose to normalize the ET based on basal canopy area because it reflected the area a tree would hold in a landscape. Normalizing the ET of the trees to a water depth measurement (centimeters) associated with a given area allowed for ET comparisons on a unit area basis and allowed for direct comparison with turfgrass species ET (centimeters). Total evapotranspiration for trees and grass were compared for the 2-year period, revealing a clear separation ($P < 0.001$) between the two groups when ET was standardized with basal canopy area (Table 3).

The trees selected within the 100-tree plot were located at different distances from the plot edge. We examined whether trees located closer to the edge of the plot used more water than trees located deeper inside the plot (differences in wind turbulence and sun exposure). Regression analysis based on all 10 species revealed that there was no correlation between distance from the center and ET on a basal canopy area basis ($P > 0.05$).

All trees but *L. indica* used less water than reference ET, as *L. indica* averaged 197 ± 42 cm annually. This species had the shortest height and smallest basal canopy area. The next two highest water users, *F. velutina* 'Modesto' and *G. tricanthos*, had the next smallest basal canopy areas, respectively. ET in centimeters is shown for *C. linearis* and *L. indica* in Fig. 2, revealing higher ET values based on a basal canopy area for *L. indica*. Water use varied in a sinusoidal fashion throughout the year with higher water use in

did positive T$_c$ – T$_a$ values occur (indicating increased levels of stress). In all cases, the average T$_c$ – T$_a$ values were negative. With regard to leaf xylem water potential, only the native *C. linearis* had statistically more positive leaf xylem water potentials than six of the other species (Table 2), with average values for all species ranging from –1.79 to –2.86 MPa.

Soil water storage. Soil water storage oscillated the opposite direction as reference ET in 9 of the ten species, as demonstrated with *F. velutina* 'Modesto' and *L. indica* (Fig. 1). This fluctuation between the soil water storage being high when reference ET was low and soil water storage being low when reference ET was high can be explained by the watering regime. Trees received water

Table 3. Hydrological balance (Hdro, evapotranspiration) and sap flow (SF, transpiration) for trees and grass in north Las Vegas with year one (Yr 1), year two (Yr2), and 2-year total (2 Yr Ttl).[z]

Plant species	Hdro cm Yr 1	Hdro cm Yr 2	Hdro 2 Yr Ttl	SF cm 2 Yr Ttl	Hdro L 2 Yr Ttl
C. linearis	45.76 ± 23.42 ab[y]	38.03 ± 15.88 ab	83.79 ± 39.29 ab	19.95 ± 12.88 a	19,025.45 ± 2,804.30 a
F. velutina 'Arizona'	42.90 ± 8.97 a	49.53 ± 5.84 bc	92.43 ± 14.81 a	53.37 ± 54.30 abc	24,444.94 ± 2,462.18 a
F. velutina 'Modesto'	88.41 ± 25.30 b	66.59 ± 13.25 c	155.00 ± 37.90 b	52.10 ± 39.76 abc	17,536.78 ± 1,922.14 a
G. tricanthos	61.70 ± 15.72 ab	60.21 ± 21.03 bc	121.90 ± 33.25 ab	50.03 ± 7.94 b	20,434.32 ± 3,883.33 a
L. indica	196.32 ± 19.89 d	196.61 ± 37.32 e	392.93 ± 89.74 d	99.48 ± 75.73 abc	22,078.17 ± 3,973.63 a
P. alba	44.05 ± 7.07 a	32.29 ± 3.99 ab	76.34 ± 11.57 a	26.87 ± 2.62 a	16,920.37 ± 2,990.73 a
P. florida	38.56 ± 19.89 a	23.92 ± 6.69 a	62.47 ± 22.67 a	112.26 ± 28.08c	18,687.67 ± 8,470.15 a
Q. virginana	51.70 ± 20.09 ab	32.64 ± 8.91 ab	84.34 ± 28.59 a	340.14 ± 269.28 c	16,405.40 ± 4,521.92 a
U. parvifolia	49.55 ± 2.30 a	33.69 ± 6.38 ab	83.23 ± 5.43 a	45.89 ± 6.48 b	18,874.68 ± 2,968.84 a
V. agnus-castus	44.66 ± 15.57 a	41.33 ± 7.56 b	85.99 ± 21.10 a	34.81 ± 18.82 ab	16,477.72 ± 3,281.03 a
C. dactylon L. F.	106.28 ± 8.77 c	106.28 ± 8.77 d	212.56 ± 17.54 c	—	—
F. arundinacea	186.35 ± 14.31 d	197.35 ± 15.56 e	383.71 ± 12.62 d	—	—
C. dactylon H. F.	209.27 ± 6.56 d	193.56 ± 6.85 e	402.83 ± 5.78 d	—	—

[z]H. F. and L. F. correspond to high-fertility and low-fertility *C. dactylon*, respectively. Hdro cm Yr 1, Hdro cm Yr 2, and Hdro 2 Yr Ttl all represent the amount of water used per basal canopy area.
[y]Different lowercase lettering associated with these average values indicates significant differences within each column at the $P < 0.05$ level.

summer months and lower water use during winter months. In the case of the high water using *L. indica*, ET rates in June and July were more than 10-fold higher than during the dormant winter/early spring period. On the basis of yearly average values, the Spearman rank correlation comparing years 1 and 2 was 0.70 at the $P = 0.02$ level. Only *P. alba* and *U. parvifolia* had statistically significant differences in ET comparing years 1 and 2, with both species having significantly lower ET values in year 2.

We found no significant correlations between ET and the physiological measurements reported in Table 2. The fact that no correlations existed between $T_c – T_a$ values (positive) and decreasing ET/sap flow was supportive of the experiment being conducted under non water stress conditions. However, stomata conductance measurements on the leaves of trees (limited data set) were found to have a significant linear correlation with increasing ET (2-year total, centimeters), with higher ET values being associated with higher conductance values (ET = 3.70 + 0.67 (conductance, mmol·m^{-2}·s^{-1}), $R^2 = 0.59$, $P < 0.001$), with the trees with the smaller canopy volumes (*L. indica*, *F. velutina* 'Modesto', *G. tricanthos*, and *V. agnus-castus*) having the highest conductance values.

Interestingly, the ET of all the trees showed a 1- or 2-month lag behind the ET$_{ref}$. This was particularly noticeable during the peak ET period for the trees in July and Aug. 2017, whereas the ET$_{ref}$ (Penman–Monteith), peaked in June. ET vs. ET$_{ref}$ linear regressions were generated by adjusting for this 1- or, in some cases 2-month, offset, aligning the ET with ET$_{ref}$. With an offset adjustment, all trees had a positive relationship between ET and ET$_{ref}$ (R^2 ranging from 0.47 to 0.76, $P < 0.001$, Table 4). Plant factors (PF = ET/ETref) were generated based on the entire 2-year monitoring period, with seven of the 10 species having a PF value that ranged from 0.20 to 0.29 (0.26 ± 0.03), with a higher value of 0.39 for *G. tricanthos*, 0.49 for *F. velutina* 'Modesto', and 1.25 for *L. indica*. Turfgrass PF values ranged from a low of 0.68 for low-fertility *C. dactylon* (historical data) to 1.22 for high-fertility *F.*

arundinacea and 1.28 for high fertility *C. dactylon*.

ET for the two grass species followed reference ET in a sinusoidal fashion as reported in Fig. 2. High-fertility *C. dactylon* and high-fertility *F. arundinacea* (Table 3) used more water than reference ET and over twice the amount reported for low-fertility C. dactylon in southern Nevada (Devitt et al., 1992). The grass ET for both species was found to be significantly correlated with ET$_{ref}$. The highest correlation was with high-fertility *C. dactylon* ($R^2 = 0.58$, $P < 0.001$). A much poorer correlation was obtained for the cool season *F. arundinacea*, which showed a 2-month ET offset in year 2, similar to what was observed for the trees ($R^2 = 0.19$, $P = 0.02$).

The one-way ANOVA results based on log transformed 2-year total ET (centimeters) standardized on basal canopy area showed *F. arundinacea* and *C. dactylon* used significantly more water than all the trees except *L. indica* ($P < 0.001$). Even low-fertility *C. dactylon* ET was significantly higher than all tree species, with the exception of *L. indica* and *F. veluntina* 'Modesto'. *L. indica* used significantly more water than all other tree species ($P < 0.001$) on a basal canopy area basis. Interestingly, *F. velutina* 'Modesto' used more water than *F. velutina* 'Arizona' ($P < 0.003$) on a basal canopy area basis associated with a 13% lower basal canopy area and 46% lower canopy volume (Table 1) but with significantly higher average conductance values (May; Table 2).

We ran backward stepwise regression analysis on the ET data to determine which morphological parameters were driving higher ET values. All morphological parameters were eliminated except % cover (log transformed, $R^2 = 0.88$, $P < 0.001$). Where % cover was estimated based on the individual tree cover relative to the unit spacing of the tree plots. In fact, a better fit occurred when % cover was plotted directly against ET and fit to a second order polynomial (ET = 633 – 1454(%cover) + 911(%cover)^2, $R^2 = 0.92$, $P < 0.001$, outlier *C. linearis* excluded). Positions on the curve were species specific, recognizing that each species would have

its own unique water regulatory mechanisms that might be influenced by planting density. To really understand the position on the curve in terms of how % cover directly influenced ET, each species would need to be grown in a similar planting density (256 trees/ha) comprised entirely of that species but at different planting dates (age) or through selected pruning (such as occurs in commercial orchards). However, it should be noted that in nine of the 10 species, the replicate with the smallest % cover had larger ET than the replicate with the largest % cover. We also incorporated the ET for oak and mesquite grown in the Devitt et al. (1994) study (not including desert willow that was a significant outlier in our current study). We only used the larger trees from the earlier study and only those trees that were irrigated at ET (0.00 leaching fraction, same as this study). The curvilinear relationship captured these earlier values on the same graph and improved the R^2 value to 0.96 [Fig. 3; ET (cm) = 632 – 1449 (%cover) + 908 (%cover)^2, $P < 0.001$].

ET vs. transpiration. Sap-flow data revealed transpiration was significantly less during summer months than ET estimates obtained with the hydrologic balance approach, revealing a seasonal oscillation pattern (Wynne, 2019) that was not as clear and distinct as the ET patterns. During the winter months, the sap-flow transpiration and the hydrologic balance ET converged, whereas during the summer months the values showed greater divergence, associated with higher irrigations and evaporation rates. The effect was more pronounced in *L. indica*, which had the smallest canopy volume and groundcover area, leading to a higher percentage of the basin area exposed to greater evaporation. During winter months, irrigation volumes were significantly less, as was ET$_{ref}$, leading to a lower evaporation component which led to a closer relationship between transpiration and ET. Although ET was typically greater than T in all but winter months, this was not the case for *Q. virginiana*. A clear contrast in ET and T was observed when *Q. virginiana* and *L. indica* were compared (Table 3) because they represented a clear contrast in size, with *Q. virginiana* being the tallest tree
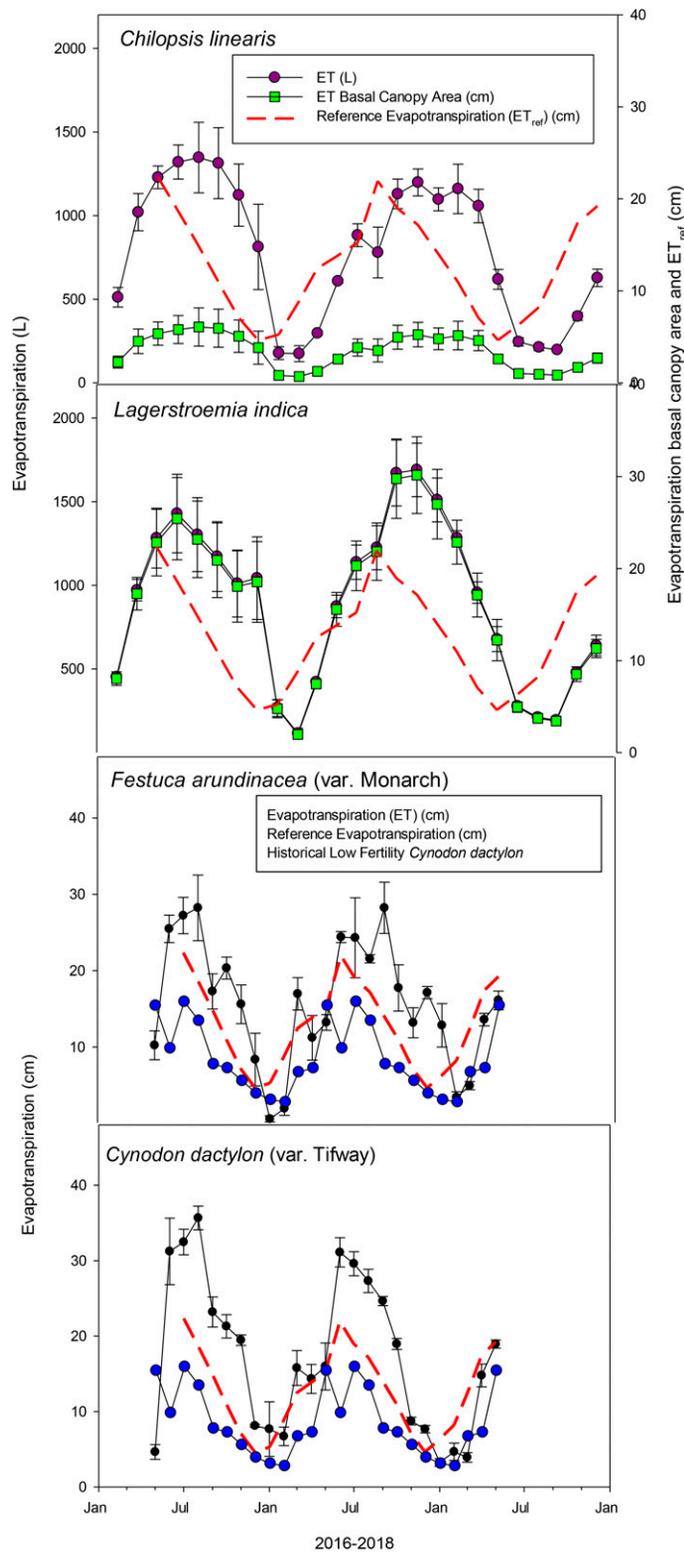
Fig. 2. Evapotranspiration (ET) of two tree species reported as total liters consumed per tree and also the mean ET standardized per basal canopy area (±1 SE bar) compared with reference evapotranspiration (ET_ref). Grass evapotranspiration is also shown for tall fescue (*F. arundinacea)* and bermudagrass (*C. dactylon*) compared with reference evapotranspiration (ET_ref) and low-fertility *C. dactylon.* Points are means with 1 SE.

with the largest trunk diameter and canopy volume (Table 1). Sapwood depth defined by the dye staining revealed an average depth of 5.75 cm for *Q. virginiana*, which was seven times greater than the average value found in

C. linearis and greater than any other species (Table 1). However, it was the smaller tree that had the highest water use rate on a basal canopy area basis (Table 3). We recognize that a single sap-flow sensor positioned at the

1-cm depth may not have adequately represented the conductive tissue for all of the tree species, especially in the case of *Q. virginiana*, where a single sensor did not provide us with the ability to assess if a sap-flow gradient existed. The fact that our *Q. virginiana* transpiration estimate exceeded ET would support the existence of a gradient that would need to be taken into consideration as demonstrated by Berdanier et al. (2016). Although there were significant correlations between ET and percent cover, no significant correlations existed between T and percent cover.

We assessed E by subtracting sap-flow (centimeters) from the hydrologic balance ET (centimeters, without *Q. virginiana*, negative outlier). Log-transformed E accounted for 81% of the variation in the 2-year ET total (centimeters), whereas a linear fit of % cover vs. E accounted for 66% of the variation in E, with higher E associated with lower % cover [E (cm) = 155 – 190 (% cover), $R^2 = 0.66$, $P < 0.001$] with a prediction of 116 cm of E at 20% cover vs. 23 cm of E at 70% cover.

Tree-to-grass water use ratios. The tree-to-grass water use ratios typically fell below a 1:1 line except for a few months, typically during the first winter period (Wynne, 2019). These higher ratios during the first winter were associated with reduced irrigations on the grasses to bring storage values down to minimize drainage. A winter irrigation adjustment was not needed during the second year. Only in the case of *L. indica* were the tree-to-grass ratios consistently above the 1:1 line, especially when compared with the projected lower water using low-fertility *C. dactylon* (maximum: 4.72, minimum: 0.52, average: 2.04, SE: 0.20), with the *L. indica* tree-to-grass ratios significantly different from all other tree grass ratios ($P < 0.001$, such as *C. linearis*, maximum: 0.94, minimum: 0.13, average: 0.45, SE: 0.52). Highest tree-to-grass ratios typically occurred during the early fall period when many of the trees responded to the lower temperatures, and vapor pressure deficit (VPD) and had higher ET values peaking after ET_ref peaked in June, whereas both *C. dactylon* (high fertility) and *F. arundinacea* (high fertility) revealed significant declines in ET during August compared with June (Fig. 2).

Discussion

We report the first ET values for mature urban landscape trees (>20 years in age) growing in the Mojave Desert. These ET values contribute to a much-needed database to be used by water managers and landscape architects to develop low-water-use landscapes in arid environments. However, we recognize that the ET of urban landscape trees will vary not only based on species but also on size, cover, planting density, climate (macro/micro), and, most importantly, by the amount of water provided. Although it would be easy to simply transfer ET values from one bioclimatic zone to another, such an approach is highly problematic and rarely

Table 4. Evapotranspiration in centimeters vs. reference evapotranspiration (ET_{ref}) for all 10 species of trees in north Las Vegas with 1-month ET_{ref} offset, except for *Quercus virginiana*, *Parkinsonia florida*, and *Prosopis alba*, which had a 2-month ET_{ref} offset. Plant factors (PF, ET/ET_{ref}) are also reported for all tree and grass species.

| Tree species	R^2	*P* value	PF
Chilopsis linearis	0.570	<0.001	0.27
Fraxinus velutina 'Arizona'	0.596	<0.001	0.29
Fraxinus velutina 'Modesto'	0.602	<0.001	0.49
Gleditsia tricanthos	0.731	<0.001	0.39
Lagerstroemia indica	0.759	<0.001	1.25
Prosopis alba	0.474	<0.001	0.24
Parkinsonia florida	0.638	<0.001	0.20
Quercus virginiana	0.519	<0.001	0.27
Ulmus parvifolia	0.474	<0.001	0.27
Vitex agnus-castus	0.582	<0.001	0.27
C. dactylon low fertility	—	—	0.68
Festuca arundinacea	—	—	1.22
Cynodon dactylon	—	—	1.28
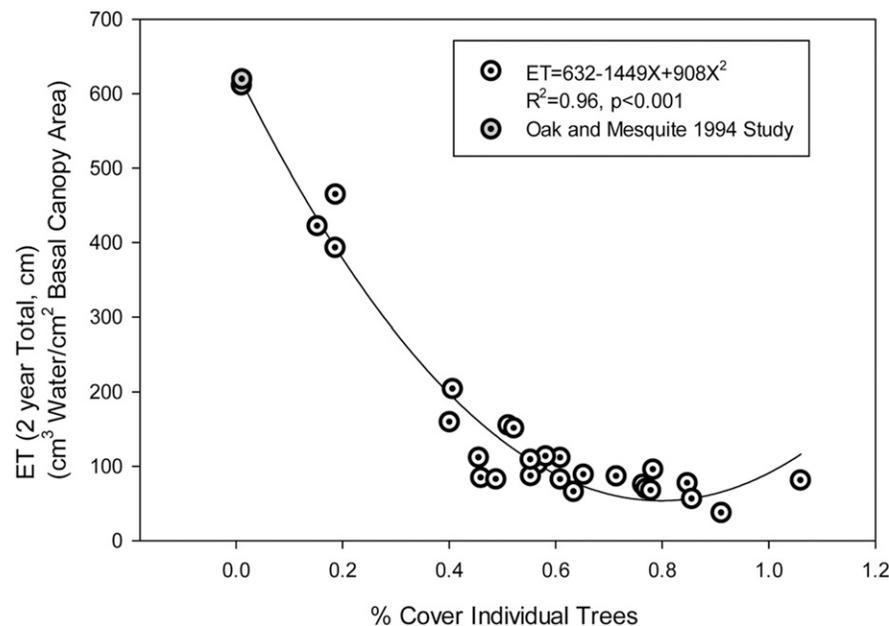
Fig. 3. Evapotranspiration of trees on a basal canopy area basis (centimeters) as a function of the % cover (% canopy area of individual tree plots).

justified (Devitt et al., 1992; Kjelgren et al., 2005; Sun et al., 2012). Our ET values were based on irrigating at ET to eliminate a drainage component in the hydrologic balance, allowing for reasonably accurate closure. Earlier studies (Devitt et al., 1994) with some of these same species demonstrated increased ET with increased irrigation volumes. Other studies (Sun et al., 2012) reported that woody perennials from arid xeric habitats categorized as low water users could actually consume as much water as mesic species when water was readily available.

We believe the ET values we report represent a lower safe level for scheduling irrigations for these tree species growing under the conditions reported (high planting density, irrigations set based on the previous week's ET), with ET tracking reference ET under non–water-deficit conditions (Sun et al., 2012). However, we did observe a 1- to 2-month offset in the tree ET relative to reference ET during the summer months. When we compared monthly maximum air temperature and VPD values in July (maxi-

mum average air temperature of 40.0 ± 3.3 °C, and a VPD of 5.97 ± 1.43 kPa) with September (maximum average air temperature of 32.7 ± 5.2 °C and a VPD of 4.31 ± 1.30 kPa), it is highly likely that greater stomata regulation (increased closure) could have been initiated reducing transpiration loss during June and July, whereas lower air temperatures and VPD later in the summer would have allowed stomata to remain more open, fueling greater transpiration to drive the offset we observed. This would be in agreement with Buwalda and Lenz (1995) that woody species would have strong atmospheric coupling and would show stomata sensitivity to high VPD, resulting in reduced transpiration under higher environmental demand.

ET was found to be highly correlated (curvilinear, $R^2 = 0.96$, $P < 0.001$) with individual tree percent cover, with higher ET (based on basal canopy area) associated with trees with smaller canopy areas. In fact, when morphological parameters were placed in a backward regression analysis, all parameters were removed except % cover. In Fig. 3, we demonstrate that the relationship between

% cover and ET also captured data from the earlier Devitt et al. (1994) study. In the earlier study, the trees were smaller with greater spacing, and although the amount of water used by the smaller trees was less, the amount lost per unit basal canopy area was greater. Trees that were smaller in stature and growing in more open areas would have allowed greater turbulence, micro advection, and a greater percentage of the canopy having sunlit leaves (Bonachela et al., 1999; Testi et al., 2004). Similar findings were reported by Devitt et al. (1998) for a riparian stand of tamarix in which 25% of the canopy was lost when the Virgin River (Nevada) changed its course but higher ET occurred, associated with a more open canopy that allowed for thermally induced turbulence.

We recognize that the planting density (256 trees/ha) was a significant factor influencing ET. A higher-density planting (park setting, orchard or forest) can result in a different response compared with an isolated tree. Nisbet (2005) stated that in general, isolated single trees in a landscape have a higher water use because of their larger canopies and greater exposure. Calder (1990) reported that thinning of forest stands often has little effect on ET due to increased canopy ventilation. Maximum ET in orchards typically occur at 60% to 70% ground shading, and ET has been found to increase at a rate about twice that of the percent ground shading (Schwankl et al., 2007). In Fig. 3, we found that ET as reported on a basal canopy areas basis stabilized when percent cover exceeded 75%, while ET rapidly increased when percent cover was lower than 45%. *L. indica* had the highest sap flux rates and some of the highest stomata conductance values associated with the lowest basal canopy area. This led to accelerated ET rates because the smaller trees were growing in more open areas, allowing solar radiation to fuel higher evaporation rates, enhance greater atmospheric exchange with canopy leaves, and allow greater horizontal micro advection (Testi et al., 2004). Pataki et al. (2011) also reported high transpiration rates for *L. indica* among 15 species studied in the Los Angeles area but noted that because of its smaller size, it did not translate into the highest water user.

As trees grow, their water use requirements increase (Devitt et al., 1994), but their water use on a basal canopy area may actually decrease, meaning that the greatest trade-off in water use between trees and grass (based on our studies) would occur with low-fertility *C. dactylon* replacing smaller trees (Devitt et al., 1995), but of course these small trees would represent only a small fraction of the landscape area. In our current study, all of the trees except *L. indica* had tree-to-grass water use ratios below 1 (whereas smaller trees in the 1994 study had ratios as high as 4), meaning that greatest water savings in urban landscapes with mature trees would occur by removing the turfgrass, not the trees—especially cool season grasses such as high-fertility *F. arundinacea* but even high-fertility warm season grasses such as *C.*

dactylon. How much the ratio would shift with individual trees in an open landscape is unknown. To further demonstrate this point, we calculated the number of each tree species that would be needed to equal the ET of the grasses covering an area of 185 m² (Wynne, 2019), realizing the limitations in this approach of not knowing how each species would respond (such as LAI) to a high planting density of 100% groundcover. In this 185-m² space, 32.5 trees of *L. indica* would physically fit, whereas 31.7 trees would have an equal ET as *F. arundinacea*; the other nine tree species would physically fit an average of 8.9 (± 1.5) trees, whereas 37.2 trees (± 4.9) would equal the ET of *F. arundinacea* and 20.6 (± 2.7) trees would equal the ET of low fertility *C. dactylon*.

Our findings, based on the experimental design reported herein, indicate that significant trade-offs between plant cover (trees vs. grass) and water consumption can occur. Additional research is needed to quantify ET of more tree and grass species to expand the concept of landscape trade-offs and to quantify water use based on isolated trees vs. trees in mixed landscapes vs. high-density tree plantings. More research is also needed to quantify the water use of trees when irrigations are set beyond actual ET to quantify the extent of excessive growth, luxury water consumption, or increased deep drainage. We also believe deficit irrigation studies are needed on trees and grasses as long as salinity is not a confounding variable. Finally, we agree with Sun et al. (2012) that percent cover is a significant and powerful variable driving ET of urban landscapes, and trees in particular. However, one must not overlook the significant influence planting density can have on the percent cover ET relationship, especially in irrigated arid environments. Pataki et al. (2011) suggested that a nonlinear feedback on transpiration exists at high canopy densities because of reduced canopy atmospheric coupling. We agree with Pataki and also believe that smaller trees within the higher planting density would be partially released from this nonlinear feedback with a different response from each species based on inherent differences in growth, sap flux density, and stomata regulation. Those species with smaller percent cover (*L. indica*, *G. tricanthos*, and *F. velutina* 'Modesto') within the planting density of our experiment (256 tree/ha) recorded the highest ET values based on basal canopy area.

Literature Cited

Allen, R., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration: Guidelines for computing crop requirements. FAO Irrigation and Drainage 56.

Berdanier, A.B., C.F. Miniat, and J.S. Clark. 2016. Predictive models for radial sap flux variation in coniferous, diffuse-porous and ring porous temperate trees. Tree Physiol. 36:932–941.

Bonachela, S., F.L. Orgaz, F.J. Villablobos, and E. Fereres. 1999. Measurement and simulation of evaporation from soil in olive orchards. Irrig. Sci. 18:205–211.

Bowman, D.C. and L. Macaulay. 1991. Comparative evapotranspiration rates of tall fescue cultivars. HortScience 26:122–123.

Brown, C., D.A. Devitt, and R.L. Morris. 2004. Water use and physiological response of tall fescue turf to water deficit irrigation in an arid environment. HortScience 39:388–393.

Buwalda, J.G. and F. Lenz. 1995. Water-use by European pear trees growing in drainage lysimeters. J. Hort. Sci. 70:531–540.

Calder, I.R. 1990. Evaporation in the uplands. Wiley, Chichester, UK.

DaCosta, M. and B. Huang. 2006. Minimum water requirements for creeping, colonial and velvet bentgrass under fairway conditions. Crop Sci. 46:81–89.

Devitt, D.A. 1989. Response of bermudagrass to varied leaching fractions, irrigation, salinity and soil types. Agron. J. 81:893–901.

Devitt, D.A., R.L. Morris, and D.C. Bowman. 1992. Evapotranspiration, crop coefficients, and leaching fractions of irrigated desert turfgrass systems. Agron. J. 84:717–723.

Devitt, D.A., M. Berkowitz, P.J. Schulte, and R.L. Morris. 1993. Estimating transpiration for three woody ornamental tree species using stem-flow gauges and lysimetry. HortScience 28:320–322.

Devitt, D.A., R.L. Morris, and D.S. Neuman. 1994. Evapotranspiration and growth response of three woody ornamental species placed under varying irrigation regimes. J. Amer. Soc. Hort. Sci. 119:452–457.

Devitt, D.A., D.S. Neuman, D.C. Bowman, and R.L. Morris. 1995. Comparative water use of turfgrasses and ornamental trees in an arid environment. J. Turfgrass Mgt. 1:47–63.

Devitt, D.A., A. Sala, S.D. Smith, J. Cleverly, L.K. Shaulis, and R. Hammett. 1998. Bowen ratio estimates of evapotranspiration for *Tamarix ramosissima* stands on the Virgin River in southern Nevada. Water Resour. Res. 34:2407–2414.

Devitt, D.A., M. Lockett, R.L. Morris, and B.M. Bird. 2007. Spatial and temporal distribution of salts on fairways and greens irrigated with reuse water. Agron. J. 99:692–700.

Devitt, D.A., K. Carstensen, and R.L. Morris. 2008. Residential water savings associated with satellite-based ET irrigation controllers. J. Irrig. Drain. Eng. 134:74–82.

Devitt, D., B. Bird, B. Lyles, L. Fenstermaker, R. Jasoni, S. Strachan, J. Arnone, F. Biondi, S. Mensing, and L. Saito. 2018. Assessing near surface hydrologic processes and plant response over a 1600 m mountain valley gradient in the Great Basin, NV, USA. Water 10(4):1–21.

Gibeault, V.A., J.L. Meyer, V.B. Youngner, and S.T. Cockerham. 1985. Irrigation of turfgrass below replacement of evapotranspiration as a means of water conservation: Performance of commonly used turfgrass. Proc. Intl. Turgrass Res. Conf. Avignon France 5:347–356.

Granier, A. 1985. Une nouvelle method pour la mesure de flux de s'eve brute dans le tronc des arbres. Ann. Sci. For. 42:81–88.

Granier, A. 1987. Evaluation of transpiration in a douglas fir stand by means of sap flow measurements. Tree Physiol. 3:309–320.

Granier, A., R. Huc, and S.T. Barigali. 1996. Transpiration of natural rain forest and its dependence on climatic factors. Agr. For. Meteorol. 78:19–29.

Jarvis, P.G. and K. McNaughton. 1986. Stomatal control of transpiration: Scaling up from leaf to region. Adv. Ecol. Res. 15:1–49.

Kjelgren, R., T. Montague, and R. Beeson. 2005. Water use and stomatal behavior of sweetgum (*Liquidambar styraciflua* L.) relative to reference evaporation in three contrasting regions. Acta Hort. 664:353–360.

Leskys, A., D.A. Devitt, R.L. Morris, and L.S. Verchick. 1999. Response of tall fescue to saline water as influenced by leaching fractions and irrigation uniformity distributions. Agronomy 91:409–416.

Levitt, D.G., J.R. Simpson, and J.L. Tipton. 1995. Water use of two landscape tree species in Tucson, Arizona. J. Amer. Soc. Hort. Sci. 120:409–416.

Litvak, E., H.R. McCarthy, and D.E. Pataki. 2012. Transpiration sensitivity of urban trees in a semi-arid climate is constrained by xylem vulnerability to cavitation. Tree Physiol. 32:373–388.

Litvak, E., N.S. Bijoor, and D.E. Pataki. 2014. Adding trees to irrigated turfgrass lawns may be a water-saving measure in semi-arid environments. Ecohydrology 7:1314–1330.

Litvak, E. and D.E. Pataki. 2016. Evapotranspiration of urban lawns in a semi-arid environment: An in-situ evaluation of microclimatic conditions and watering recommendations. J. Arid Environ. 134:87–96.

Litvak, E., K.F. Manago, T.S. Hogue, and D.E. Pataki. 2017. Evapotranspiration of urban landscapes in Los Angeles, California at the municipal scale. Water Resour. Res. 53:4236–4252.

McPherson, E.G., J.R. Simpson, and M. Livingston. 1989. Effects of three landscapes on residential energy and water use in Tucson, Arizona. Energy Build. 13:127–138.

McPherson, E.G., J.R. Simpson, Q. Xiao, and C. Wu. 2008. Los Angeles 1 million tree canopy cover assessment. General Technical Report PSW-GTR-207. U.S. Dept. of Agr., For. Serv. Pac. Southwest Res. Stn.

McPherson, E.G., J.R. Simpson, Q. Xiao, and C. Wu. 2011. Million trees Los Angeles canopy cover and benefit assessment. Landsc. Urban Plan. 99:40–50.

Nisbet, T. 2005. Water use of trees. FCIN065. Forestry Commission, Edinburgh, Scotland.

Nouri, H., S. Beecham, F. Kazemi, and A.M. Hassanli. 2013. A review of ET measurement techniques for estimating the water requirements of urban landscape vegetation. Urban Water J. 10:247–259.

Nouri, H., E.P. Glenn, S. Beecham, S.C. Boroujeni, P. Sutton, S. Alaghmand, B. Norri, and P. Nagler. 2016. Comparing three approaches of evapotranspiration estimation in mixed urban vegetation: Field based remote sensing based and observational-based methods. Remote Sens. 8(6):492.

Nowak, D.J., R.E.I. Hoehn, D.E. Crane, L. Weller, and A. Davila. 2010. Assessing urban forest effects and values, Los Angeles urban forest. Resour. Bull. NRS-47. U.S. Department of Agriculture, Forest Service, Northern Research Station, Newton Square, PA.

Pataki, D.E., H.R. McCarthy, E. Litvak, and S. Pincetl. 2011. Transpiration of urban forests in the Los Angeles metropolitan area. Ecol. Appl. 21:661–677.

Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. Proc. R. Soc. Lond. A Math. Phys. Sci. 193:120–145.

Peters, E.B., J.P. McFadden, and R.A. Montgomery. 2010. Biological and environmental controls on tree transpiration in a suburban landscape. J. Geophys. Res. 115:G04006.

Peters, E.B., R.V. Hiller, and J.P. McFadden. 2011. Seasonal contributions of vegetation types to suburban evapotranspiration. J. Geophys. Res. 116:GO1003.

Schiavon, M., A. Pedroza, B. Leinauer, D.L. Suarez, and J.H. Baird. 2017. Varying evapotranspiration and salinity level of irrigation water influence soil quality and performance of perennial ryegrass (*Lolium perenne* L.). Urban For. Urban Green. 26:184–190.

Schwankl, L.J., T.L. Prichard, B.R. Hanson, and R.B. Elkins. 2007. ANR Publication 8212, University of California Cooperative Extension.

Southern Nevada Water Authority. 2018. Restricting outdoor water use. 1 Feb. 2018. <https://www.snwa.com/importance-of-conservation/restricting-outdoor-water-use/index.html>.

Shearman, R.C. and J.B. Beard. 1973. Environmental and cultural preconditioning effects on the water use rate of *Agrostis palustris* Huds., cultivar Penncross. Crop Sci. 13:424–427.

Stevenson, D.S. 1989. Irrigation subsurface return flows and water use in lysimeters containing apple trees. Can. J. Soil Sci. 69:769–778.

St. Hilaire, R., M.A. Arnold, D.C. Wilkerson, D.A. Devitt, B.H. Hurd, B.J. Lesikar, V.I. Lohr, C.A. Martin, G.V. McDonald, R.L. Morris, D.R. Pittenger, D.A. Shaw, and D.F. Zoldoske. 2008. Efficient water use in residential urban landscapes. HortScience 43:2081–2092.

Sun, H., K. Kopp, and R. Kjelgren. 2012. Water-efficient urban landscapes: Integrating different water use categorizations and plant types. HortScience 47:254–263.

Testi, L., F.J. Villalobos, and F. Orgaz. 2004. Evapotranspiration of a young irrigated olive orchard in southern Spain. Agr. For. Meteorol. 121:1–18.

Wright, L., D.A. Devitt, M.H. Young, J. Gan, B. Vanderford, S. Snyder, and M. McCullough. 2012. Fate and transport of 14 pharmaceutical and personal care products in an irrigated turfgrass system. Agron. J. 104:1244–1254.

Wullschleger, S., P.J. Hanson, and D.E. Todd. 2001. Transpiration from a multi-species deciduous forest as estimated by xylem sap flow techniques. For. Ecol. Mgt. 143:205–213.

Wynne, T. 2019. Tree to grass water use ratios; assessing turfgrass high water use in the urban landscape. MS thesis, Univ. of Nevada, Las Vegas. 30 Nov. 2019. <https://digitalscholarship.unlv.edu/thesesdissertations/3705?utm_source=digitalscholarship.unlv.edu%2Fthesesdissertations%2F3705&utm_medium=PDF&utm_campaign=PDFCoverPages>.

Zajicek, J. and J. Heilman. 1991. Transpiration by crepe myrtle cultivars surrounded by mulch, soil and turfgrass surfaces. HortScience 26:1207–1210.