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Full Length Research Paper

Mixed landscape water demand and drainage in a subtropical-monsoonal climate varies with irrigation frequency and season

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Abstract

We used drainage lysimeters to study water balance and plant growth of mixed (woody plant-turf) landscapes irrigated at three rates of root zone water depletion based on local reference evapotranspiration (ET_O) in a subtropical-monsoonal climate: slow/dry (60%), intermediate (75%) and fast/wet(90%) of ET_O. Planting design for each lysimeter was identical: a *Magnolia virginiana* tree imbedded in St. Augustine grass (*Stenotaphrum secundatum*) turfgrass bordered by two *Viburnum odoratissimum* shrubs grown as a hedge. Landscape monthly actual evapotranspiration (ET_A) was calculated as the difference between inputs (irrigation and precipitation) and output (drainage). Magnolia (height, projected canopy area, and trunk diameter) and viburnum (height and canopy volume) growth was measured every three weeks. Total drainage over three years from the 0.6 depletion (driest) treatment was 20 and 45 cm for the dry and wet season, respectively, half that of the 0.9 depletion (wettest) treatment. The dry treatment had the lowest ET_A both seasons, and average dry season Plant Factors ($PF=ET_A \div ETo$) was about 15% lower than the wet season (0.76 versus 0.98). Plant growth was largely unaffected by irrigation-depletion treatments. For subtropical climates, dry season irrigation scheduling based on a mixed landscape PF of 0.75 is reasonable to maximize growth following transplanting. Once established, dry season irrigation schedules can be based on a 0.6 PF value to maintain performance while minimizing drainage. Irrigation of mixed landscapes during the monsoonal wet season is only needed during exceptional dry periods.

Keywords: Drainage lysimeter, monthly ET_A, Plant Factor, plant growth, *Viburnum odoratissimum, Magnolia grandiflora, Stenotaphrum secundatum.*

INTRODUCTION

Urban landscapes have value, but sustaining that value often depends on supplemental irrigation to stay healthy. Landscapes in arid and/or seasonally dry climates typically require seasonal routine irrigation. Landscapes in humid climates with high summer rainfall may require irrigation during short dry periods in the rainy growing season. Landscapes in any climate require irrigation following transplanting until the root system can establish into ambient soil (Caron and Kjelgren, 2016), particularly when surrounded by pavement (Koesera et al., 2014) with high foliage energy loading (Montague and Kjelgren, 2004). Finally, landscapes with inherently

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limited root zones and exploitable water due to compacted field soil, or in containers and green roofs (Layman et al., 2016; Rayner et al., 2016) are typically irrigated.

Scheduling when and how much to irrigate in all these landscape situations to satisfy plant water demand is now a must in an increasingly water limited world. Scheduling landscape irrigation first depends on reasonably accurate estimates of plant water demand. The approach adapted from agriculture to landscapes is using an empirically derived correction factor, known as a Plant Factor (PF; actual water use÷ETo) to adjust downward local reference evapotranspiration (ET_O) for a given plant type (Kjelgren et al., 2016). Kjelgren et al. (2016) reviewed studies on estimating landscape plant water demand, largely for temperate arid to semi-arid climates. Studies of landscape water demand in humid, subtropical climates are few, mostly focused on individual woody plants (Koesera et al., 2014; Shober et al., 2013), and absent for combined turf and woody plants. As such, the few extant studies of combined woody plant-turf landscapes are in temperate climates, showing PF ranges from 0.3-0.9, 0.2-0.5, and 0.5-1.2 for woody plants, perennials, and turf species under well-watered conditions, respectively (Sun et al., 2012). A greater understanding of water demand of combined landscapes in humid, subtropical climates is important because of characteristic long, dry winters warm enough for plant growth, with seasonally high evaporation rates and irrigation needs. Even the summer monsoon season experiences periodic dry breaks where irrigation may be needed in these climates.

The objective of this study was to determine optimum PF values that achieve acceptable performance for combined woody plant and turf landscapes in subtropical Central Florida. We used a water balance approach with nine large drainage lysimeters based on three assumed root zone water depletion levels to assess plant growth and water use over three years after establishment to extract appropriate Plant Factor values.

MATERIALS AND METHODS

Lysimeter Design

Nine water-sealed, concrete-block landscape lysimeters (13.3 m^2--3.35m x3.96 m) were constructed in a long row at the UF-IFAS Mid-Florida Research and Education Center in Apopka, FL. Each lysimeter was 1.45 m deep along the outside edge with a sloping floor that reached a maximum center depth of 1.52 m and spaced three meters apart within the row. The lysimeter drainage system was designed around a central junction box over a center drain hole with a sock-covered, 10.2 cm corrugated drainpipe extending to diagonal corners. The bottom of each lysimeter was covered with approximately 61 cm of rock, textile cloth, and coarse sand to ensure drainage remained constant over the duration of the study. Lysimeters were then filled with 80 cm of the native sandy topsoils: a mixture from the Candler (hyperthermic, uncoated Lamellic Quartzipsamment), –Apopka (loamy, siliceous, subactive, hyperthermic Grossarenic Paleudult) association and Tavares (hyperthermic, uncoated Typic Quartzipsamment)–Milhopper (loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudult) associations. These soils have deep A horizons, and subsequent layers by depth differ in organic matter content but not sandy texture, so we were confident that the soil mixtures in lysimeters reasonably represented local drainage. In August 2009, lysimeter soil was leveled to 8 cm below the top edge, then plants were installed.

Installation

Backfill soil around the woody plant root balls was well irrigated to ensure good contact between root balls and the soil at planting; excess soil was removed from lysimeters. Each lysimeter had identical plantings that consisted of 75% turfgrass (9.95 m^2) and 25% mulched area with woody plants. Woody species were one magnolia tree (*Magnolia grandiflora* L. 'D.D. Blanchard') and two sweet viburnum shrubs (*Viburnum odoratissimum* Ker Gawl.), whose mulched area occupied 10% and 15%, respectively, of the initial total lysimeter area. Both species are common in SE U.S. landscapes. The magnolia was planted centered east–west and off-center to the south 0.75 m in each lysimeter within the 1.3 m^2 tree well, and two viburnums were located in a 2 m^2 (1 x 2 m) rectangular bed in the NE corner of the lysimeter. Each magnolia was approximately 1.8 m tall with a mean caliper width of 38 mm as measured at 0.15 m above ground level. They were transplanted from 0.5m root control bags (High Caliper Growing Systems, Oklahoma City, OK) on 9 Sept. 2009. A 1.15-m by 1.15-m area around each magnolia was maintained turfgrass free and mulched with ground wooden pallet mulch. Additional mulch was added to the area as needed. Magnolias were not pruned after planting. Two sweet viburnum shrubs were planted within the 1 x 2 m mulched area and were pruned into a hedge. St. Augustine grass [*Stenotaphrum secundatum* (Walter) Kuntze 'Floratam'] sod was cut from a local sandy soil in late September 2009 and installed to cover the remaining non-mulched surface area the next day. All turfgrass and woody ornamental species were considered fully established by the end of May 2010 when data collection began.

Weather and Climate Data

Daily rainfall, temperature and relative humidity were recorded daily at midnight by an on-site weather station located within 50 m of the experimental site. Wind was measured with an anemometer (014 A; Met One, Grants Pass, OR, USA) at 2 m above ground level. Incoming solar radiation was measured with a pyranometer (LI-200X; Li-Cor Inc., Lincoln, NE, USA). Weather data were transferred to a datalogger (CR1000, Campbell Scientific, Inc., Logan, UT, USA) that controlled the irrigation system. Daily ETo was calculated by the on-site weather station using the Penman–Monteith equation with resistance (Allen et al., 2005). Historical daily rainfall and evapotranspiration (Hargreaves and Allen, 2003) data from 1949 to 2018 was obtained from the Clermont 9 S weather station (Latitude: 28.0958, Longitude: -81.0023, about 40 km southwest of the study site) downloaded from Utah Climate Center - Utah State University.

Plant Maintenance and Growth Measurement

Viburnum were installed as two individual plants where plant canopies merged to a single hedge 1.5 m tall by the end of the first year. Thereafter they were pruned every 3 weeks as needed to maintain the hedge crown shape. Magnolia trees were not pruned during the study. Turfgrass was mowed to a height of 8 cm, as needed, beginning 1 June 2010 and ending 24 May 2013. Mowing was biweekly, except during the hot and rainy season (June through August), when it was weekly. Mowing ceased December through February due to occasional frost and slow growth rates. All turfgrass clippings and pruned woody plant material were removed from the lysimeter. Turfgrass clippings and pruned viburnum branches were dried and dry mass was recorded for each lysimeter during the three-year period.

Treatment effects on woody growth were assessed differently for magnolia and viburnum. For magnolia, trunk circumferences (TC) at 0.15 m above ground were measured every three weeks as well as tree height (HT) and crown diameter, which was collected in two cardinal directions (N-S and E-W) and used to calculate projected crown area (PCA). PCA of magnolia increased mainly in mid-spring with a limited shoot flush early in fall each year. For viburnum, crown dimensions were measured as N-S width × E-W width to give PCA, and then crown height was measured and multiplied by PCA to give crown volume (VO). Increments in growth for magnolia from 1 June 2010 to 31 May 2013 were calculated as increased TC, PCA, and HT. For viburnum, measurement of each individual plant was recorded before the two shrubs merged, thereafter the hedge was measured as one unit. Averaged PCA and VO of viburnum for each lysimeter was used to calculate growth increment.

Irrigation Setup and Treatments

An irrigation system was installed in each lysimeter before planting. Turfgrass irrigation was delivered through six pop-up spray heads (PROS-06-10A; Hunter Industries, Inc., San Marcos, CA, USA) with approximate flow rates of 13.5 to 15.5 $Lmin^{-1}$ at pressures ranging from 275 to 414 kPa; quarter spray heads were located in the lysimeter corners and full circle heads located in the middle of the lysimeter. Viburnum and magnolia irrigation were delivered through a 19mm black polyethylene tubing trunk line outfitted with a 172-kPa pressure regulator. Two 0.3 m high tree stakes with 189 L h^{-1} nozzles (magnolia) or four stakes with 102 L h^{-1} nozzles (viburnum), all with inverted cone sprayer nozzles (Jain Irrigation Inc., Fresno, CA, USA) were placed around the shrubs. Turfgrass and woody ornamental plant irrigation were controlled by separate valves. A water meter (C700-SF, Elster-Amco, Ocala, FL, USA) with an electronic counter (32 counts L^{-1}) was installed above each valve to measure volume of irrigation applied. Irrigation was controlled by a data logger that processed weather station data (model CR 1000, Campbell Scientific, Logan UT).

Irrigation frequency for each lysimeter was based on estimated daily water loss (ET_A) in depth units from each lysimeter derived from ETo, depletion rate, and projected canopy surface areas (PCA) for each plant species according to following equation:

(1

$$ETa^{0.6,\ 0.75,\ 0.9} = ETo \times DR^{0.6,\ 0.75,\ 0.9} \times (A_T + A_{PC-M} + A_{PC-V})/A_L$$

Where DR is the treatment rate that root zone water was depleted: 0.9, 0.75, and 0.6 of daily ET_O. Higher depletion rate (0.9) meant more rapid use of stored root zone water, more frequent irrigation and wetter soil; conversely, lower depletion level (0.6) meant infrequent irrigation and drier soil. A_T was the turfgrass area, and as previously defined A_{PC-m} was the magnolia PCA, and A_{PC-V} was viburnum PCA. Daily ET_A was then subtracted from the previous days' root zone water content assumed to be the top 30 cm of soil. The depth of water in the top 30 cm root zone was measured at 19 mm, based on water holding capacity (field capacity after drainage minus the wilting point of water content at -1.5 MPa) of 0.65 mm water per mm of the sandy textured soil, measured from previous water release curve. When cumulative ET_A exceeded 19 mm water holding capacity, an irrigation event was triggered. On days of rain prior to an irrigation event, depth of rainfall was subtracted from cumulative ET_A, delaying irrigation. If rainfall exceeded 19 mm, it was assumed that root zone water was full and cumulative ET_A reset to zero also delaying irrigation.

Irrigation frequencies were the same for lysimeters of the same treatment but varied among treatments such that 0.9 depletion rate treatment had the highest irrigation frequency and 0.6 depletion rate had the lowest. Irrigation amount was the volume of water needed to refill the 19 mm root zone corrected for surface area of turf, and PCA of magnolia and viburnum. Irrigation application was not corrected for distribution non-uniformity.

A key assumption is that magnolia and viburnums transpiring leaf areas were equivalent to their projected canopy areas (A_{PC-M} and A_{PC-V}, respectively). Due to growth, magnolia and viburnum transpiring leaf areas increased over time such that magnolia PCA was larger than the mulched area around the trees. This meant that applied water volumes were slightly greater than an irrigation volume based solely on total lysimeter area (A_L) that was constant at 13.27 m^2. However, this approach was more accurate over the three years of data collection.

Daily Leachate Volume Quantification

Each lysimeter drained into a dry well assembly, consisting of an upper 1.5L collection vessel that drained into a lower weighing vessel. The weighing vessel was suspended from a 22.7kg load cell (Interface Inc., Scottsdale, AZ, USA). The assembly was installed below the 5.08cm lysimeter drain and was housed inside an enclosure adjacent to each lysimeter to exclude rainfall. Drainage from each lysimeter was determined by the load cell using an automated process that controlled the flow of water through the dry well assembly when a minimum of 1 L of water had accumulated in the lower collection vessel. Volume of drainage water from each lysimeter was recorded by a data logger during each weighing event, with the running drainage total was exported daily at 0500 h.

Data and Statistical Analysis

Monthly drainage volume and irrigation volume was converted to depth based on lysimeter surface area. Monthly ET_A in depth units for each lysimeter was estimated based on the following equation on the volume of water applied to turf (V_T) and woody (magnolia and viburnum) species ($V_{M\&V}$) from their respective flow meters with measured drainage volume (V_d) corrected for lysimeter surface area:

(2)

$$Monthly\ ET_A = Monthly\ (V_T + V_{M\&V} - V_d)/A_L + rainfall$$

This is a simplified water balance equation without considering change in soil water storage. Since Florida's sandy soils retain little water, again 19 mm per 300mm (0.3 m) depth being a common water holding capacity, soil water storage is minimal compared to plant water use on a monthly or yearly scale. Regional climate was shown by plotting probability of rain by day of year, and on days of rain average depth for that date. Weather during the study was graphed as ET_O and rainfall by day, and then monthly lysimeter water use, ET_A, and depth of applied irrigation and drainage. Total three-year drainage was then regressed against total irrigation applied over the study were, and monthly ET_A was related to monthly ET_O and rainfall to assess the weather parameters most likely to govern water use.

The experiment was a completely randomized design with the three irrigation-depletion rate treatments with three replicates randomly assigned within the row of lysimeters. Differences among years and treatments were evaluated separately with one-way ANOVA, and where significant, pairwise comparisons were made using the R software (version R×64.3.5.2) and then LSD multiple range test with a significance level of 0.05 was used for pairwise comparisons.

RESULTS

Historical Climate

Florida has a typical monsoonal climate, with a wet season from roughly May to October and dry season from November to April (Fig. 1a-1b). The wet season with the highest probability and depth of rainfall is from mid-May to end of October, with peak rainfall likelihood and amount from July to September. During the dry season from November-April,the lowest probability and depth of rainfall during November and December. A small peak of rainfall depth often appears in late March and beginning of April in the dry season. Although wet season rainfall probability is nearly always higher than the dry season, rainfall depth during the shoulder periods could be lower than various dry season periods. Furthermore, during the peak wet season of July and August, sometimes rainfall depth could be lower than that in April of dry season (Fig.1b).

Daily ET_O normally peaks mid-April to mid-May, averaging about 5 mm per day for about four months till mid-August, then decreasing from September until a January minimum (Fig.1c). Daily variation in ET_O is highest during the peak wet season, as frequent afternoon thunderstorms and clouds reduce plant water use. Conversely, during rainfall breaks in midsummer with long days and high temperatures daily ET_O approaches that of more arid climates, above 6 mm per day, driven by the amount of incoming solar rather variation in humidity.

Weather and Water During Study Period

Weather during the study period generally mirrored that of historical climate (Fig. 2a). As per the norm, daily ET_O was highest May to August, in the range of 0.5-0.6 cm, and lowest December to February, 0.15-0.2 cm.

Table 1. Yearly, dry season and wet season ET_A/ETo for drainage lysimeters with turf and woody plant cover over 3 years when irrigated with assumed 0.9 PF, 0.75 PF, and 0.6 PF.

	Depletion Rate	Year 1	Year 2	Year 3	Average
Yearly Total	0.9	0.93±0.03[Aa]	0.94±0.07[Aa]	0.97±0.14[Aa]	0.95±0.08[Aa]
	0.75	0.82±0.05[Bb]	0.85±0.01[Bb]	0.95±0.04[Aa]	0.87±0.03[ABb]
	0.60	0.77±0.05[Bb]	0.78±0.01[Cb]	0.92±0.03[Aa]	0.82±0.02[Bb]
Dry season	0.90	0.70±0.06[Ab]	0.90±0.05[Aa]	0.92±0.18[Aa]	0.84±0.09[Aab]
	0.75	0.64±0.02[ABc]	0.77±0.01[Bb]	0.89±0.04[Aa]	0.77±0.02[ABb]
	0.60	0.60±0.05[Bc]	0.62±0.00[Cbc]	0.80±0.03[Aa]	0.67±0.01[Bb]
Wet season	0.90	1.12±0.04[Aa]	0.94±0.08[Ab]	1.06±0.11[Aab]	1.05±0.05[Aab]
	0.75	1.00±0.11[ABa]	0.85±0.01[ABb]	1.05±0.04[Aa]	0.96±0.05[ABab]
	0.60	0.95±0.07[Bb]	0.83±0.01[Bc]	1.04±0.03[Aa]	0.93±0.04[Bb]

Note: Different uppercase letters indicate the significance among treatments for each year and each season, different lower case letters indicate significance among years.

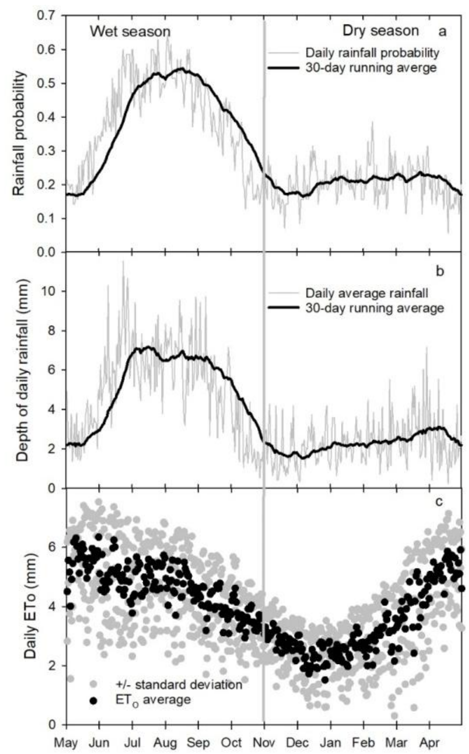

Fig. 1. Historical regional monsoonal climate, 1949-2018 from Clermont, Florida, approximately 40 km southwest of the study site. A) probability of precipitation (number of days with precipitation divided by total years of data) by day of year (grey lines) and previous 30 day running average (black line); B) average depth of precipitation on days with precipitation by day of year (gray lines) and previous 30 day running average (black line); C) average daily ETo ± standard deviation (Penman Monteith equation) by day of year. Vertical line bisecting all three graphs separate the wet season (May-October) from the dry season (November-April).

The 2011-12 dry and wet seasons were exceptionally drier: 72% and 24% lower, respectively, than the 70-year average. Monthly ET_A calculated by water balance of the different root zone water depletion treatments followed monthly trends of ET_O: low January and February, but increasing from March onward, reaching peak water use during May to September, then progressively decreasing thereafter. Even during the subtropical winter, temperatures are sufficient for transpiration and often growth, depending on plant growth habit.

Monthly ET_A was typically highest at the 0.9 depletion while the 0.6 treatment the lowest (Fig. 2b). For isolated daily rain events over 40 mm, most drainage was completed the same day or the day after, due to the highly permeable/low water holding capacity sandy soils. Such storms were associated with tropical disturbances, or more likely slow-moving thunderstorms. Monthly water balance calculations for water use were divided by calendar month that occasionally resulted in under/over ET_A estimations where drainage overlapped to the next month.

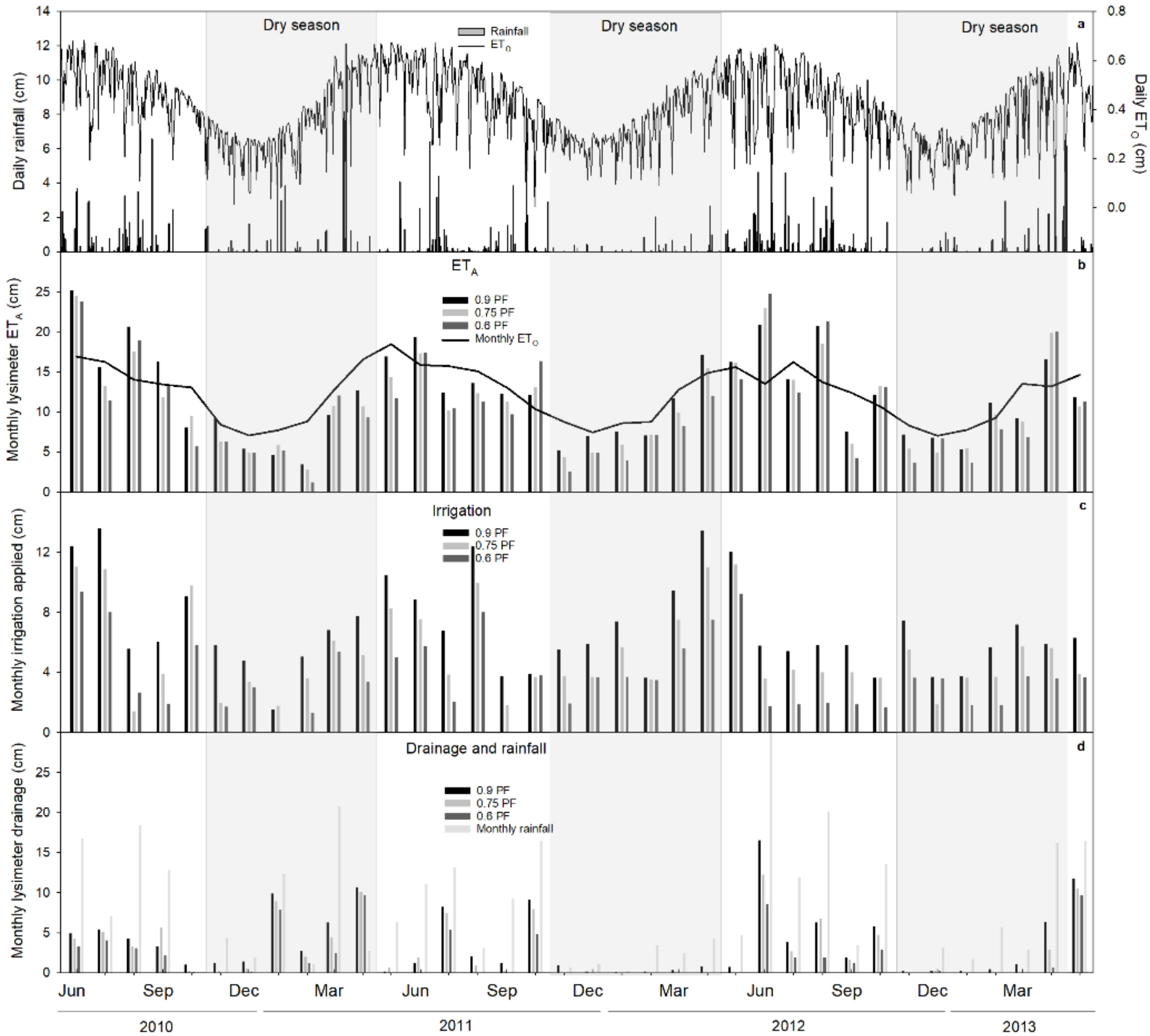

Fig. 2. Water balance parameters for large drainage lysimeters in a monsoonal climate: (a) Daily precipitation and ETo,(b) monthly lysimeter ETa(n=3) and ETo (solid line), (c) monthly irrigation applied (n=3), (d) monthly lysimeter drainage and rainfall (n=3), for 0.9, 0.75, and 0.6 root zone water depletion rate treatments during the experimental period from June 2010 to May 2013. Vertical shaded areas represent the November-April dry season.

This occurred mostly late spring and during the summer months, making aggregated seasonal totals more representative of actual water use.

Overall, irrigation amounts were high later in dry season, concurrent with high ETo. Irrigation occurred every month for all depletion rate treatments except for 0.6 in January 2011 and Sept. 2011 (Fig. 2c). Irrigation amount was highest in the spring of 2011 and 2012, and lowest in April and May of 2013 due to exceptionally high rainfall that year. However, dry breaks during the wet season can trigger substantial irrigation, as seen in July 2010, October 2010, and August 2011. Irrigation volume was always highest for the 0.9 depletion treatment, while reciprocally the 0.6 treatment had less frequent irrigation and so lower total applied water.

Drainage occurred when monthly rainfall was highduring any season (Fig. 2d). For example, a wet January-April 2011 dry season drainage was essentially the same as the somewhat dry 2011 wet season. Combined irrigation and rainfall meant that drainage was greatest under the 0.9 treatment, and again the 0.6 treatment the least. When dry season rainfall was low, there was almost no drainage from all three plant factor treatments, especially forthe 0.6 depletion treatment, indicating irrigation applied to each lysimeter was based on plant need and soil holding capacity, and did not have muchover-irrigation during the experimental period.

Cumulative Drainage

Cumulative total irrigation and drainage over the three-year study provides a clearer picture of seasonal and treatment differences (Fig. 3a-b). As expected, over both seasons, faster root zone water depletion rate triggered frequent irrigation and increased drainage, but the relationship between seasons differed. Somewhat unexpectedly, cumulative wet season irrigation was, on average, 26% greater than during the dry season across all three depletion rate treatments, 0.7-1.4 versus 0.6-1.1 meters, respectively. Greater wet season irrigation was due to four months of ET_O in the 4-6 mm per day range and enough days or partial days without rain that estimated depletion rates triggered irrigation more frequently than dry season where ET_O ranged from 2-3 mm per day over four months. Consequently, wet season drainage was 2-2.5 times more than dry season drainage, and given greater rainfall that kept soils wet with less storage capacity, more water drained during the wet season relative to irrigation, 67% over the three treatments. By contrast, only 38% of applied irrigation water was lost through drainage. Ultimate differences in drainage were stark: over a meter of water was lost as drainage with higher irrigation frequency (0.9 depletion rate) during the wet season, while drainage at lower irrigation frequency (0.6 depletion rate) during the dry season was five-fold less, just 0.2 m. Taking this analysis a step further by accounting for landscape utilization of rainfall, the frequent irrigation treatment was least efficient, utilizing only a bit over half. By contrast, the less frequent treatment (0.6 depletion rate) was more efficient, utilizing over ¾ of rainfall over the three years.

Monthly ET_A versus ETo, Rainfall

Monthly landscape water use (ET_A) relationship to increasing atmospheric water demand (ET_O) and additional supply (rainfall) varied with irrigation treatment (Fig. 4). Overall ET_A was weakly related ET_O, somewhat more so at the wetter (0.9) depletion treatment (R^2=0.57), but less so (R^2=0.36) at more infrequent, drier irrigation (0.6) treatment (Fig. 5a-c). With more frequent irrigation (0.9 depletion treatment) surface evaporation was likely greater, while less frequent irrigation may have triggered some degree of mild water stress and partial stomatal closure – essentially deficit irrigation (Geerts and Raes, 2009) that would partially decouple water use from ET_O and result in more variable ET_A. When forced through the origin/zero, the slope of this relationship is functionally the Plant Factor-PF (Kjelgren et al., 2016; see Table 1).
Conversely, the relationship between monthly ET_A and rainfall was closer with less frequent irrigation (Fig. 5d-f): with more frequent irrigation (0.9 treatment) the relationship to ET_A was weaker (R^2=0.37), but was stronger as rainfall increased (R^2=0.66) (Fig. 4d-4f).The curvilinear relationship between monthly ET_A and rainfall at the0.9 irrigation frequency suggests that when monthly rainfall reached a certain amount, monthly ET_A stopped increasingdue to lack of soil water storage and excessive rainfall draining out of root zone, rather than contributing to plant water use, or was evaporated. But with less frequent irrigation (0.6 depletion treatment) rainfall may have increased landscape water use by mitigating mild water stress, increasing stomatal conductance and transpiration.

Yearly and seasonal ET_A/ETo

Actual water use divided by standardized evaporative demand, ET_A/ET_O, is the combined landscape PF. Plant Factor values varied most between seasons, but less so among years and treatments (Table 1). Yearly average PF values over the study period differed among treatments, from a low of 0.82 at low irrigation frequency (0.6 treatment) to 0.95 for the 0.9 depletion rate; these values are essentially the same as the slopes in Figure 4a-4c. However, while PF values for the wetter (0.9 depletion) treatment were constant all three years, probably due to higher surface evaporation, values for 0.75 and 0.6 irrigation frequency treatments increased over the duration of the study, and were not different from the 0.9 irrigation frequency treatment by year 3. Lower PF values during years 1 and 2 for the 0.6 and 0.75 depletion treatments are likely due to the combination of woody plants less surface evaporation and root systems not being fully established and so unable to fully exploit soil water.
Average differences in PF values by season were large. Over three years wet season PF values ranged from 0.83-1.12 for 0.6 and 0.9 irrigation frequency treatments, respectively, varying widely from year to year. Over the three years, wet season ET_A/ET_Ovalues for the 0.9 depletion treatment were higher than the other two treatments, but only by about 10%.Not so for PF values during the dry season; PF values rose roughly 25% over the three years across all treatments, likely due to greater woody plant root establishment and crown sizes. Again, the 0.6 depletion treatment appears to function as deficit irrigation, not fully re-saturating the root zone capacity as rapidly as the other two treatments, thus limiting transpiration (Chai et al., 2016).

Growth

Differences in growth increment within irrigation treatments were greater than differences among depletion rates at the end of the study (Fig.5). Less frequent irrigation and possibly mild water stress did not limit magnolia height, as variance among trees was low

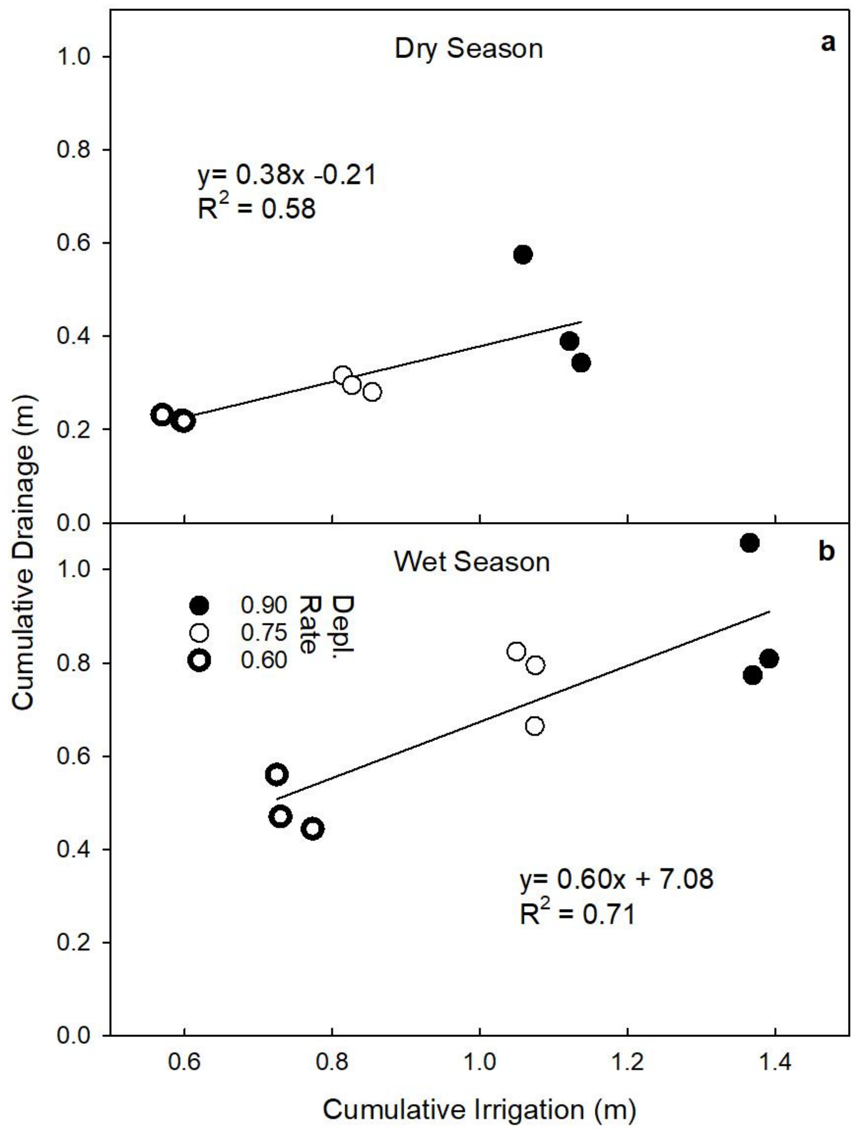

Fig. 3. Relationship between total woody plant (one *Magnolia grandiflora* and two *Viburnum odaratissimum*) lysimeter drainage and irrigation during the monsoonal dry season (**a**) and wet season (**b**) over the three-year study period (turf not included) when irrigated at 0.9, 0.75, and 0.6 root zone water depletion treatments (n=3).

(Fig. 5a). However, trunk growth and projected canopy area (PCA) did not differ among irrigation treatments due to large tree-to-tree variation within the three replicates. Growth increment variance was also large for viburnum over the three-year study period, likely due to crown pruning to shape a functional hedge (Fig. 5b). Viburnum dry matter did not differ among irrigation frequencies, but variability among replicates was high. By contrast, viburnum PCA and crown volume was greatest at the intermediate, 0.75 depletion rate treatment.

The picture of how irrigation frequency affected growth increment has more resolution when related to total water use (Fig. 6). Of the frequently irrigated (0.9 treatment) magnolia and viburnum, one plant each simply did not add as much leaf area and biomass, respectively, as the other two plants in the treatment; this translated to greater within-treatment variation. The intermediate irrigation treatment (0.75) and somewhat similar total ET_A had one plant each that either grew more (magnolia) or less (viburnum) than the other two replicates that added to the variation. Differences in turf dry matter was largely unrelated to ET_A (Fig 6c). Overall, more frequent irrigation and so greater ET_A over three years resulted in a marginal increase in growth.

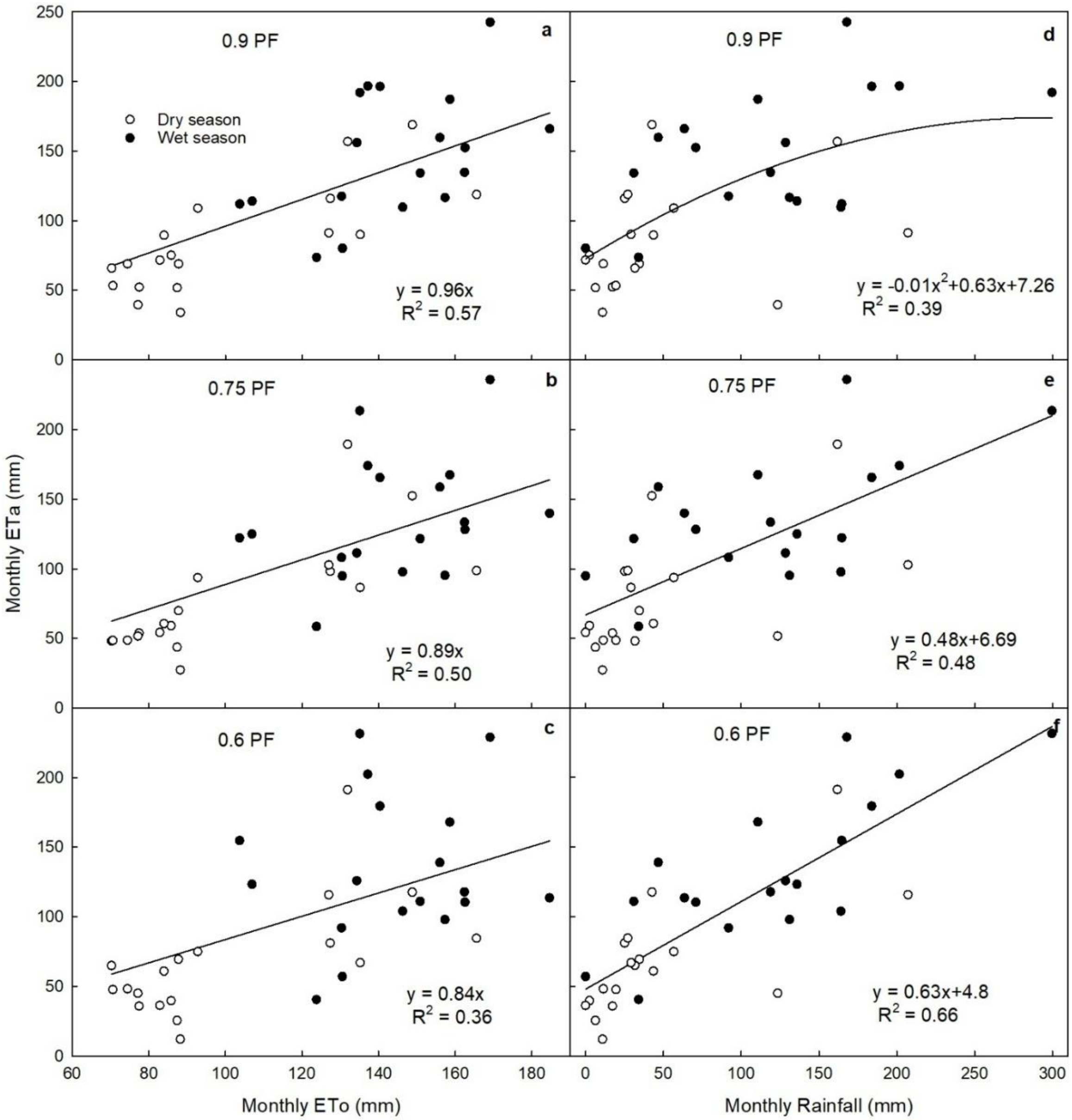

Fig. 4. Monthly plant water use (ETa; derived from a water balance approach) from mixed woody plant-turf landscapes drainage lysimeters in a monsoonal climate versus reference evapotranspiration (ETo) and rainfall: (a-c) relationship between monthly ETa and monthly ETo (trendline forced through the origin), (d-f) monthly ETa relationship to monthly rainfall over three years (n=36) for 0.9, 0.75, and 0.6 root zone water depletion (frequent, intermediate, infrequent irrigation) treatments.

DISCUSSION

Florida is wet, depending on year and location. Annual rainfall totals from north to south range from 100-170 cm, and year-to-year variation falls in the same range, but seasonal differences can be large (Black, 1993). North Florida rainfall is more evenly distributed throughout the year while central and south Florida have more typical subtropical, monsoonal climates where November-April dry season rainfall falls to about 25% of the yearly total. Because of warm temperatures in these regions, landscape plants are typically irrigated during the dry season, but even during the wet season, dry periods with high ET_O can result in landscape water shortages without irrigation.

Weather during this study largely fell within normal rainfall and ET_O variations of central Florida's climate with some exceptions. Wet season rainfall all three years was lower than the long-term average for wet season rainfall, and in particular 2011 July-August rainfall of 2011 was only 40% of the long-term average, dry enough that irrigation would be necessary. Dry season

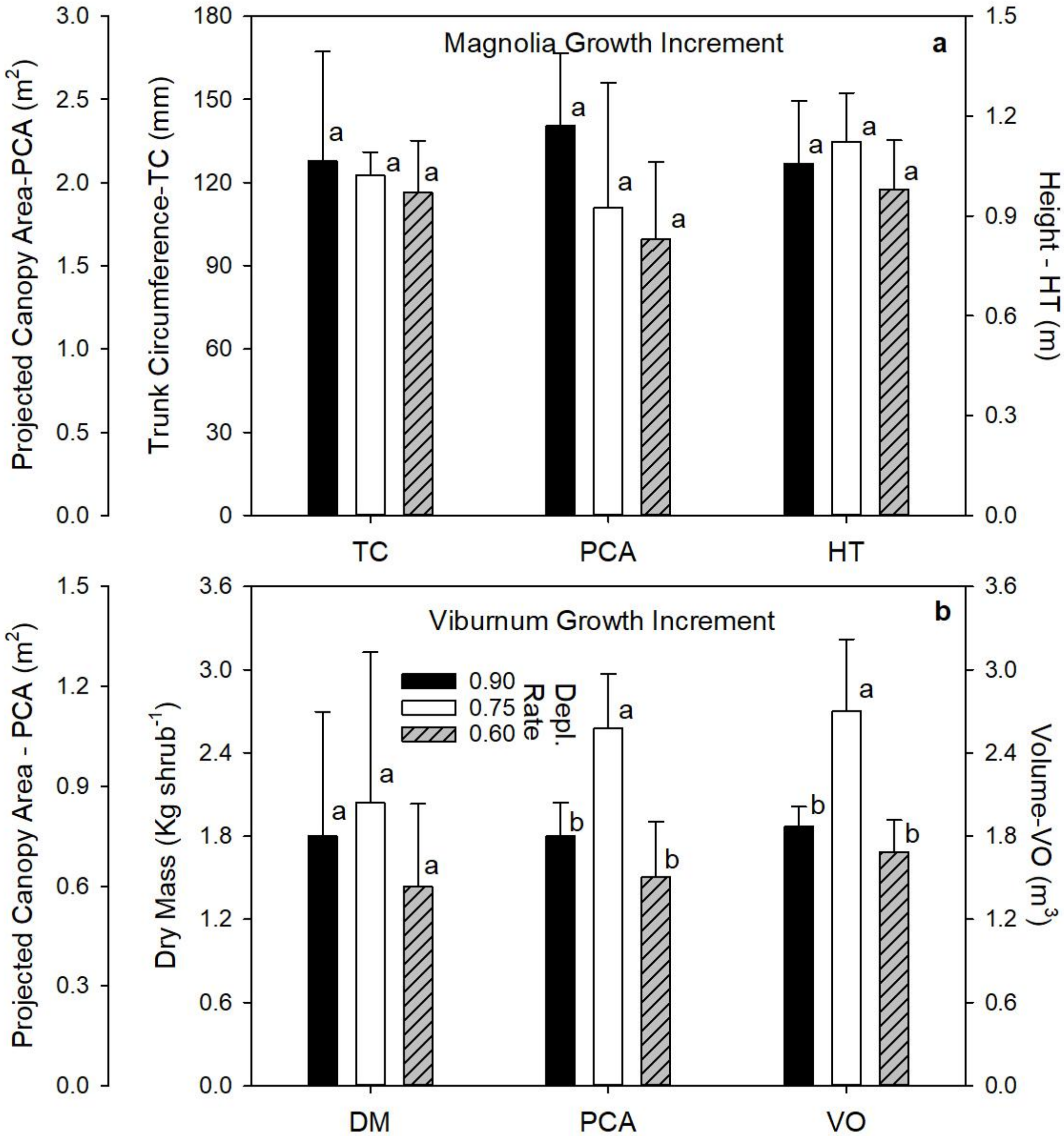

Fig. 5. Mixed turf-woody plant landscape water use and measured drainage from large draining lysimeters: (a) growth increment for magnolia and (b) viburnum over the three-years experimental period for 0.9, 0.75, and 0.6 root zone depletion (frequent, intermediate, infrequent irrigation) treatments (n=3).

rainfall was even more variable, as during the 2011-12 dry season rainfall was about 70% lower than the long-term average, and several high rainfall events January-March 2011 produced significant drainage in even the driest treatment. Given this variability, monsoonal wet and dry seasons are blurred generalizations compared to the sharply delineated seasons of an arid climate that requires a different approach to applying PF values to landscape water conservation.

In dry climates, PF values for separate landscape plant types are appropriate and practical to use for precision irrigation during regular summer drought (Sun et al. 2012). Distinct PF's by plant type allows hydrozoning by water demand, relatively precise irrigation control, and more efficient and targeted water conservation (Kjelgren et al., 2016). Unlike arid climates where mulch is the key ground cover in low water landscapes, in a monsoonal climate such as central and south Florida, irrigated and non-irrigated turfgrass can be a practical landscape surface cover, even in water conserving landscapes. Kjelgren et al. (2016) suggested that woody plant PF values are in the same general range during peak irrigation (0.6-0.7 relative to ETo) as warm

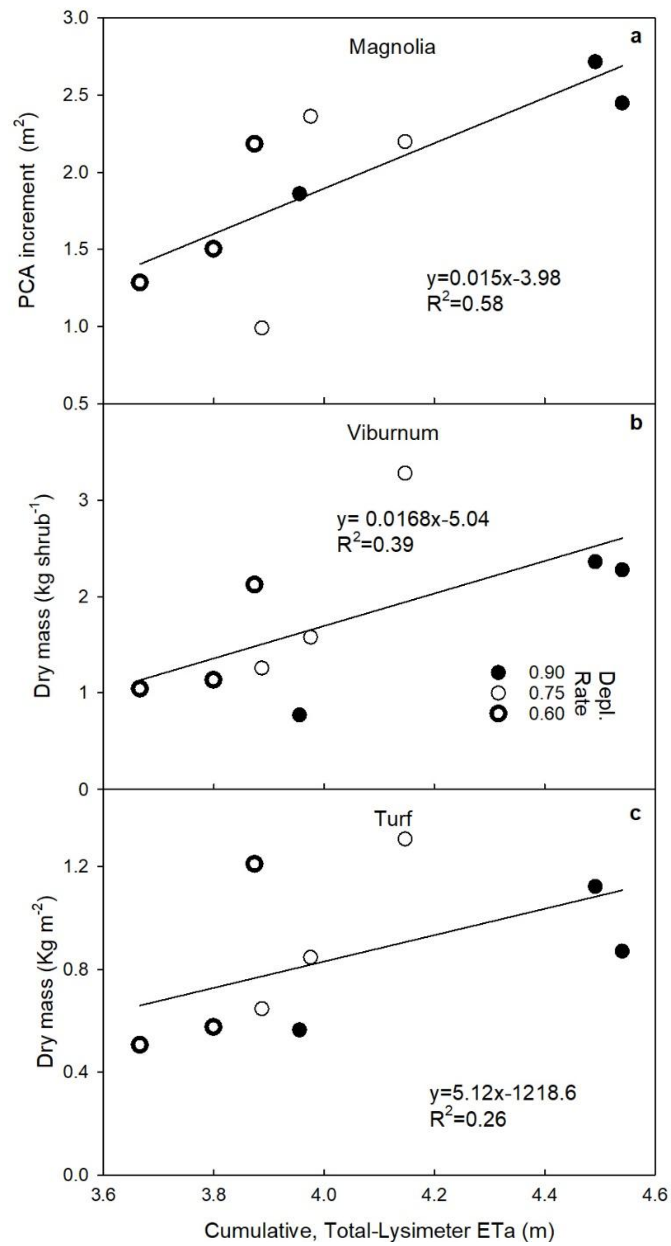

Fig.6. Relationship of mixed turf-woody plant landscape growth to cumulative, total (turf and woody plant) water use (ET_A) from large draining lysimeters in a monsoonal climate: (a) magnolia projected canopy area (PCA) versus ET_A, (b) viburnum branch prunings versus ET_A, dry mass of mowed turf versus ET_A over three years during the experimental period for 0.90, 0.75, and 0.60 root zone water depletion (frequent, intermediate, infrequent irrigation) treatments (n=3).

season turfgrass PF values in a monsoonal climate (Romero and Dukes, 2016; Wherely et al, 2015). Given that turfgrass is the go-to ground cover in monsoonal climate, trees are commonly imbedded in turf, and with shrub beds irrigated the same. The results from the present study support suggestion of Kjelgren et al. (2016) that mixed turf-woody plant, water conserving landscapes in a monsoonal climate have sufficiently compatible root zone water depletion rates, and so a general landscape PF can be used in scheduling irrigation timing during peak irrigation. The more critical drivers for water conserving landscapes in a monsoonal climate are landscape age, irrigation season and leaching.

We suggest that water managers charged with landscape water conservation in subtropical climates such as Florida develop policies to discourage wet season landscape irrigation. We have shown that wet season PF values in frequently irrigated landscapes are high, most likely due to elevated rainfall frequency and intensity that drives greater surface evaporation. High wet season ET_A and PF values link closely to major water quality issues (Dukes et al., 2018), especially for irrigated landscapes where wet season commercial fertilization is banned by some municipalities to protect ground water (Volusia County, 2020). Well drained soils are prone to high drainage and leaching (Duncan et al., 2016), and sandy, well-drained soils are ubiquitous in Florida. Our study suggests any wet season irrigation results in two-thirds of irrigation water draining below the root and leaching nutrients and other soluble compounds into groundwater; restricting summer irrigation would greatly reduce leaching in Florida's soils. There are exceptions. Wet season irrigation would be necessary for new landscapes with limited root zone development where frequent but limited depth irrigation is required until establishment, usually around a year (Scheiber et al., 2007), and during extreme dry periods, such as in 2011. Irrigation can be efficiently managed in both situations by using water budget-ET irrigation controllers that can appropriately limit frequency and amount based on weather and soil properties (Davis and Dukes, 2016).

Given that the data presented here for turf and shrubs showed minimal impact on growth, albeit with limited statistical strength, we consequently recommend a dry season PF of 0.6 for established landscapes be used in weather-based irrigation controllers as a balance between acceptable growth and minimal drainage. A 0.6 PF is within the 0.5 to 0.7 range reported for south Texas mixed turf/woody landscapes also using drainage lysimeters (Pannkuk et al., 2010), and similar to the turf and woody plant PF's Kjelgren et al (2016) suggested for humid climates. However, since magnolia PCA and trunk growth was reduced at lower irrigation frequency, and PF's the first two years were lower both seasons, we recommend a PF of 0.7 to 0.75 for newer landscapes being established with woody plants, consistent with recommendations by Kjelgren et al. (2016).

We also suggest that mixed landscapes in a humid climate with trees imbedded in turf may be more efficient than hydrozoning woody plants and turf separately. Interestingly, in an arid climates, tree cover imbedded in turfgrass reduced overall transpiration of the combined turf-tree system from shading of turf and tree stomatal sensitivity to high VPD (Litvak et al., 2014). The data from this study (Fig. 5c) suggests that mild stomatal closure during the dry season during lower humidity days at 0.6 PF irrigation may indeed reduce overall mixed landscape transpiration. More importantly, shading of turf by tree canopy cover will unlikely increase mixed landscape water use, and deeper rooting of woody plants may be able to scavenge water that drains below the turf root zone, reducing leaching. Related, infrequent and deep deficit irrigation of mixed landscapes have several benefits: better anchored tree roots, greater root zone storage capacity of unpredictable rainfall that would minimize leaching, and greater drought avoidance by both trees and turf during extended dry periods.

Finally, the PF values, ratio of drainage to irrigation by season, and rainfall utilization enhances the ability of water retailers in monsoonal climates to better manage urban water. Plant Factors are the key to developing water allocations monitoring excess use by commercial and residential consumers based on landscaped area, local ET_O and water billing data (Glenn et al., 2015). These factors and ratios can also be used in water planning in a monsoonal climate to model changes in future demand as temperatures and ET_O increase and rainfall patterns change.

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CONFLICT OF INTEREST

The authors declare no competing financial interests.

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