

Daily Evapotranspiration of *Guzmania* ‘Irene’ and *Vriesea* ‘Carly’ Bromeliads Produced in a Shaded Greenhouse

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Abstract. Bromeliads are important ornamental foliage plants, but until now, their daily water use during production was unknown. Using a canopy closure model developed for container-grown woody ornamental plants, in this study we investigated actual evapotranspiration (ET_A) of *Guzmania* ‘Irene’ and *Vriesea* ‘Carly’ from tissue-cultured liners grown in 15-cm containers to marketable sizes in a shaded greenhouse. The mean daily ET_A of *Guzmania* ‘Irene’ ranged from 4.02 to 66.35 mL per plant, and the mean cumulative ET_A was 16.66 L over a 95-week production period. The mean daily ET_A of *Vriesea* ‘Carly’ varied from 3.98 to 59.89 mL per plant, and the mean cumulative ET_A was 15.52 L over the same production period as the *Guzmania* cultivar. The best-fit models for predicting daily ET_A of the two bromeliads were developed, which had correlation coefficients (*r*²) of 0.79 for *Guzmania* ‘Irene’ and 0.68 for *Vriesea* ‘Carly’. The success in the model of ET_A for both bromeliads suggested that the canopy closure model was equally applicable to container-grown ornamental foliage plants produced in greenhouse conditions. The daily ET_A and cumulative ET_A values represent research-based information on water requirements, and, when applied, could improve irrigation practices in bromeliad production. This study also showed that roots per se of the two epiphytic bromeliads were able to absorb water and nutrients from a peat-based container substrate and support their complete life cycles.

The Bromeliaceae family comprises more than 3000 species across 58 genera that are largely native to tropical North and South America (Stevens, 2013). Their exotic appearance, graceful symmetry, and potential for year-round flowering make bromeliads among the most sought-after plants in the world (Henny and Chen, 2003). Among them, *Aechmea* Ruiz & Pav., *Cryptanthus* Otto & A. Dietr., *Guzmania* Ruiz & Pav., *Neoregelia* L.B. Smith, *Nidularium* Lem., *Tillandsia* L., and *Vriesea* Lindl. are important ornamental foliage plants (Chen et al., 2005). It is estimated that nearly 60 million potted bromeliad plants are sold annually worldwide, of which 60% are *Guzmania* (Vanhouette et al., 2016) and 15% are *Vriesea* cultivars (Vanhouette et al., 2017).

Bromeliads have many unique characteristics, including epiphytism, water-absorbing leaf trichome, tank habit, and crassulacean acid metabolism (CAM), that enable them to survive under various harsh environmental

conditions (Leroy et al., 2016). More than 60% of bromeliads are epiphytes (Zotz, 2013). Epiphytic bromeliads have two life forms: tank bromeliads, whose leaves spiral and arrange to form a rosette cup or tank where they accumulate water and organic debris, and atmospheric bromeliads, whose leaves are narrow and do not serve as a reservoir (Benzing, 2000; Givnish et al., 2007). Leaf hair or foliar trichomes are specialized for water and nutrient absorption and are called absorptive trichomes (Zotz, 2013).

Both *Guzmania* and *Vriesea* are tank bromeliads and considered to be C₃ plants (Pierce et al., 2001) with exception of some *Guzmania* that are facultative CAM species (Freschi et al., 2010). Their growth and development under protected culture may be different from their wild habitats. Commercially, they are produced in soilless substrates under climate-controlled greenhouses and supplied with ample water and nutrients. A recent study showed that roots of two cultivars of *Vriesea* are able to absorb much more water than trichome in commercial production conditions (Vanhouette et al., 2017). Roots of *Vriesea* have been shown to possess root hairs, a vascular system, and an endodermis (Proenca and Sajo, 2008; Reinert and Mereilles, 1993), implying that the roots are capable of taking up water and nutrients. Gas exchange and plant growth of *Guzmania lingulata* (L.) Mez. fertigated through roots

were comparable with those fertigated through tank (Silva et al., 2017).

With current commercial production practices, irrigation of bromeliads has been primarily based on growers’ experience. A common problem with the production of container-grown plants has been overirrigation, resulting in not only poor aeration in container substrates but also nutrient leaching (Chen et al., 2001). This holds true in bromeliad production, where daily water requirements have not been quantified for any bromeliad species. To increase irrigation efficiency, Beeson (2004) proposed a canopy closure model for estimating ET_A of container-grown woody ornamental plants as a basis for precision irrigation. Based on the relationships of ET_A, potential evapotranspiration (ET_O), and projected canopy area (PCA) of a given species, a water need index (WNI) or plant factor (Kjelgren et al., 2016) is calculated, which is a function of canopy closure of a group of plants, relating individual plant ET_A to plant size and canopy ventilation and radiation (Beeson, 2005). Daily ET_O was calculated using the Campbell Scientific version of the Penman–Monteith equation, whereas ET_A was determined by an autonomous weighing lysimeter system (Beeson, 2011). The model has been used to quantify daily ET_A of several woody ornamental plants including *Ligustrum japonicum* (Beeson, 2004), *Viburnum odoratissimum* (Beeson, 2010a, 2010b), *Raphiolepis indica* (Beeson, 2012), as well as foliage plants *Asplenium nidus* L. and *Chamaedorea elegans* Mart. (Chen and Beeson, 2013), and *Calathea* G. Mey. ‘Silhouette’ and *Stromanthe sanguinea* Sond. (Beeson and Chen, 2018). Irrigation of container-grown plants based on daily water use has been documented to reduce nursery runoff volume and nutrient load without reducing plant growth (Hagen et al., 2014; Pershey et al., 2015).

The objectives of this study were to determine ET_A of *Guzmania* and *Vriesea* from tissue-cultured liners grown in 15-cm containers to marketable sizes in a shaded greenhouse and to develop models to predict daily ET_A rates. It is anticipated that such effort could provide research-based information for improving irrigation efficiency during bromeliad production.

Materials and Methods

Experimental location. This study was carried out in an 80% shaded greenhouse at the University of Florida’s Mid-Florida Research and Education Center (MREC) in Apopka. A Florida Automated Weather Network (FAWN, <https://fawn.ifas.ufl.edu/>) station at MREC is about 46 m east of the shaded greenhouse. The station provided readings of air temperatures at three elevations (0.6, 1.8, and 9.1 m), soil temperature, wet bulb temperature, dew point, relative humidity, rainfall, and wind speed every 15 min daily as well as daily evapotranspiration outside the greenhouse. The outside ET_O was calculated based on the Campbell

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Scientific Program (Campbell Scientific, 1991) which uses the full ASCE Penman–Monteith equation (Jensen et al., 1990).

Data collection system. The miniature weighing lysimeter system described by Beeson (2011) was used in this study. The system was composed of a control/data collection board connected to mini lysimeters. The control board consisted of a CR10X data logger, SDM-AM16-32 multiplexer, and SDM-CD16AC relay control module (Campbell Scientific Inc., Logan, UT) for receiving and storing data from the mini-lysimeters. Each mini-lysimeter included a load cell (SSM-50-AJ; Interface Inc., Scottsdale, AZ) suspended from a miniature tripod with a plant support suspended from the load cell. All load cells were calibrated with a seven-point curve using known masses. The data logger program recorded the mass of each lysimeter every half hour and stored it for later retrieval. At midnight, the program determined that day's ET_A for each lysimeter as the difference between mass at 0500 HR and midnight. There was no transpiration between midnight and 0500 HR. ET_A was calculated by hand using the half hour lysimeter data as described by Beeson (2006) when needed.

Plants were watered through a drip irrigation system to allow a 10% leachate fraction. Water was supplied through self-fashioned rings of pressure compensated drip tubing (Netafilm USA, Fresno, CA). As supplied, pressure compensating emitters were arranged in 30.5-cm intervals along the length of the tubing. Lengths containing four emitters were cut and rolled to form two loops, which were joined by a T-barb. These fit snugly into the top of each container. Loops were connected to a 19-mm polyethylene tubing using equal lengths of 6 mm tubing. The Christensen's Coefficients of Uniformity were determined for 15 loops from plants on each bench. The mean coefficient was 0.94 and ranged from 0.93 to 0.96. Typical application rates per bench were 187 mL·min⁻¹.

Bromeliad plant production. Tissue cultured liners of *Guzmania* 'Irene' and *Vriesea* 'Carly' were transplanted singly into 15-cm containers (1.6 L) filled with a peat-based substrate composed of 60% Canadian peat, 20% vermiculite, and 20% perlite by volume. Plants were fertilized by top dressing 5 g of a controlled-released fertilizer (CRF) (Osmocote 19N–2.18P–7.47K, 8–9 months; The Scotts Co., Marysville, OH) per container 3 weeks after potting. The same amount of the CRF was applied 42 weeks later. The experiment was arranged as a completely randomized block design with four replications. In each block, 15 plants of a species were arranged in five rows with three plants per row in an offset pattern and spacing of 30 cm between pots. The center plant was placed in a suspension-weighting lysimeter, and the four closest plants to the lysimeter plant were designated as the interior plants for repeated canopy measurements. Plants were grown in a shaded greenhouse under

a maximum photosynthetic active radiation of 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

Air temperature, relative humidity, wind, and solar radiation required for calculation of reference evapotranspiration (ET_O) were collected with an automated Weatherhawk weather station (Campbell Scientific, Inc.) inside the middle of the greenhouse 50 cm above the lysimeter tripods. The algorithm used to calculate ET_O was the same as that used in more robust outside weather stations based on Campbell Scientific equipment (Campbell Scientific, 1991). This was installed to evaluate the hypothesis that although the use of the Penman–Monteith equation inside a greenhouse violates the basis of Penman–Monteith, the thermodynamic associations of heat and random movement of water molecules within leaves and plant canopies would still mimic that of leaves outside nonetheless.

Data collection. Data collection was initiated within a week after transplanting. Canopy measurements of widest width, width perpendicular to the widest width, and average height were recorded every 3 weeks on the lysimeter plants and adjacent four plants for each replication. The two widths of each plant were multiplied to estimate the two-dimensional PCA (i.e., canopy footprint). When PCA was multiplied by the average height, canopy volume, or growth index, was estimated (Henny et al., 2009), assuming the three-dimensional canopy resembled a rectangular box. Plant water-use efficiency was calculated as total dry matter produced (g) by actual amount of water used (ET_A) (Stanhill, 1987).

Modeling plant water use. ET_A , ET_O , and PCA were used to evaluate the suitability of the percent canopy closure (%CC) model (Beeson, 2004, 2010a, 2010b) for determining water use of greenhouse-grown bromeliads. To summarize, %CC at each measurement was calculated by adding half the PCA of each of the four border plants to the PCA of the lysimeter plant and dividing the sum by allocated bench space for each plant (929 cm² in this study). Because plants

were not respaced, canopies could become overlapped with plant growth. Thus, overlapping could result in calculation of %CC greater than 100%. For each lysimeter plant, ET_A was recorded for 7 d and converted to a depth by dividing with its average PCA (cm²). ET_A (cm) was then normalized by dividing with its corresponding ET_O (cm) each day, and then averaged over the 7 d to calculate WNI using the equation of [WNI = (ET_A /PCA)/ ET_O] for each lysimeter plant at each measurement date. Calculated WNI values of the four lysimeter replicates for each date were plotted against their corresponding %CC values. The plot was fitted to a three-parameter exponential decay curve using SigmaPlot (Version 10; SPSS Inc., Chicago, IL). An equation for the nonlinear line was derived using a three-level inverse polynomial equation (Version 10; SPSS Inc.).

Results

Reference evapotranspiration. The ET_O (ET_{O-GH}) values in the shaded greenhouse were \approx 12% of that outside the shaded greenhouse as measured by the FAWN station. Solar radiation in the shaded greenhouse was around 15% that of outdoor conditions, and relative humidity was normally higher inside the greenhouse. Although there was no measurable wind, air movement occurred during most afternoons from early spring until late fall due to operation of evaporative cooling fans. Temperatures in the shaded greenhouse were also more moderate than outside conditions, with minimums set at 18.3 °C for heating and 32.2 °C for evaporative cooling. ET_O was highest in April and May (days 90 to 150), declined the rest of the period with the onset of summer rains, then shorter days. In Central Florida, April and May tend to have the highest vapor pressure deficits (VPD) due to mostly clear skies and low humidities resulting from the near absence of rainfall. Evaporative cooling during this period often is insufficient to maintain low VPD.

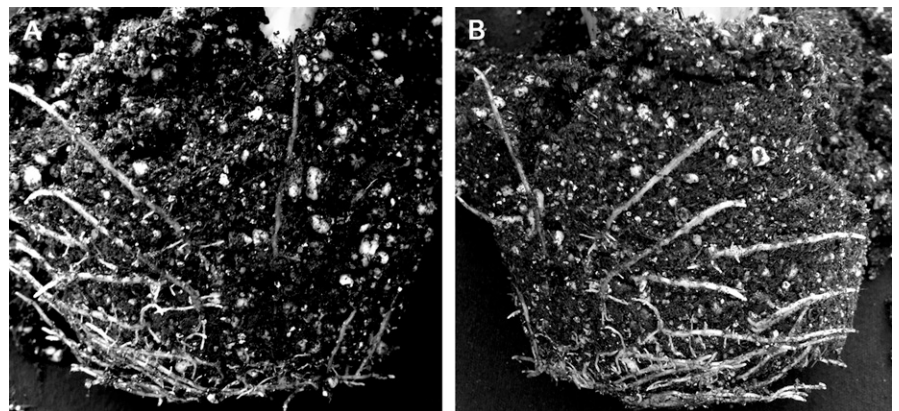


Fig. 1. Roots of *Guzmania* 'Irene' (A) and *Vriesea* 'Carly' (B) 3 months after growing in 15-cm containers filled with a peat-based substrate. Both plants had well-developed roots when watered through drip irrigation to the substrate not into the tank or cup.

Root growth. To assess root growth of two bromeliad species watered through drip irrigation, plants were pulled from containers 3 months after potting. Both species had well-established roots systems. Many roots had

penetrated the substrate, with white, healthy roots appearing in the interface of container wall and substrate, and some had root hairs (Fig. 1).

Shoot growth. *Guzmania* 'Irene' was potted in Nov. 2006 and harvested in Sept. 2008,

when they had reached a size suitable for commercial marketing. Leaves were glossy green with a mean length of 40 cm. Canopy heights and widths of *Guzmania* 'Irene' increased linearly (data not shown), but its growth index increased polynomially (Fig. 2A). *Guzmania* 'Irene' produced 10 to 15 fuchsia-magenta bracts, which are modified leaves. At harvest, mean canopy height and width were 45.6 cm and 71.9 cm, respectively. It had a mean of 33.3 leaves and a total leaf area of 4,067.4 cm². Shoot and root fresh weights were 176.2 g and 12.7 g, and corresponding dry weights were 29.1 g and 2.4 g, respectively. *Guzmania* 'Irene' had a water use efficiency of 1.9 (Table 1).

Vriesea 'Carly' was potted concurrently with *Guzmania* 'Irene' in Nov. 2006 and harvested in Sept. 2008 when a marketable size was attained. 'Carly' has green and stiff leaves with a mean length of 16 cm. Canopy heights of *Vriesea* 'Carly' increased linearly, and widths increased polynomially (data not shown). Growth index increased linearly (Fig. 2B). *Vriesea* 'Carly' has yellow and red flower spikes. Mean canopy height and width at the time of harvest were 22 cm and 26.3 cm, respectively. 'Carly' produced 28.9 leaves with a total leaf area of 1583.5 cm². Shoot and root fresh weights were 48.7 g and 9.6 g; shoot and root dry weights were 8.5 g and 2.0 g, respectively. Water use efficiency of *Vriesea* 'Carly' was 0.7 (Table 1).

Actual evapotranspiration. The mean cumulative ET_A for *Guzmania* 'Irene' was 16.66 L per plant during the entire production period. At the beginning of the experiment, mean ET_A ranged from 5.91 to 17.74 mL per plant per day (Fig. 3A). Beginning in Feb. 2007, mean ET_A increased more than 2-fold over the next 50 d, ranging from 23.66 to 35.49 mL per day. During the summer months of 2007, mean ET_A averaged around 29.57 mL per day but ranged from 6.21 to 51.37 mL per day during this period. The variability in ET_A is likely due to highly fluctuation in cloud cover during the summer rainy season. Mean ET_A began declining in August (day 300) to reach a low in Dec. 2007, comparable with that of the first December in 2006. Mean ET_A again began increasing from late January 2008 to the summer of 2008. Mean ET_A was quite variable during this period, ranging from 4.02 to 66.35 mL per day. The decline in Aug. 2008 mirrored that measured the previous year.

The mean cumulative ET_A value was 15.52 L for *Vriesea* 'Carly'. Initial daily ET_A for individual plants ranged from 7.64 mL to 32.93 mL (Fig. 3B). This declined quickly to 4.48 to 11.83 mL per day by the middle of

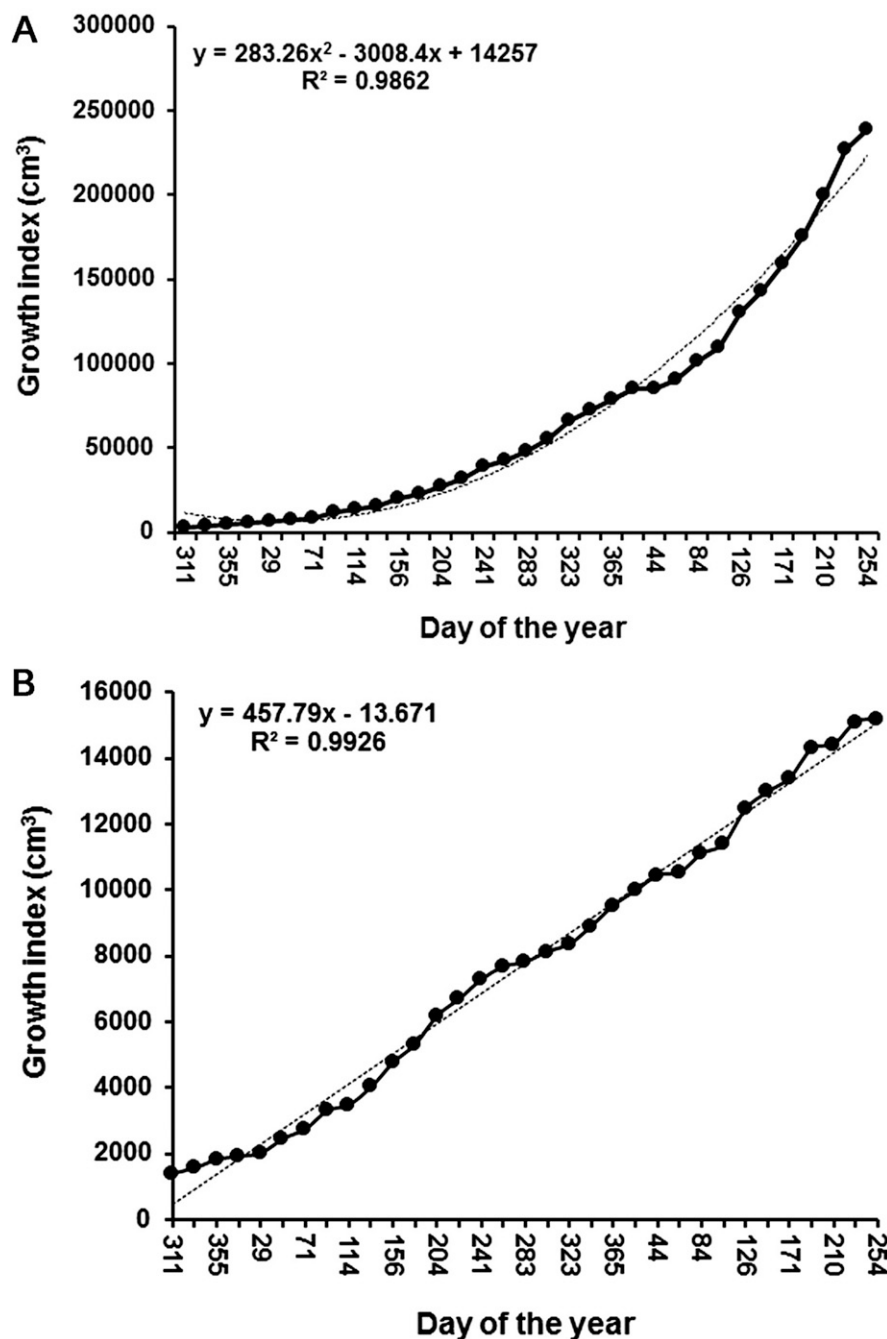


Fig. 2. Growth indices (cm³) of *Guzmania* 'Irene' (A) and *Vriesea* 'Carly' (B) grown in 15-cm containers from tissue-cultured liners to marketable sizes. The equations are based on the best-fit dash line.

Table 1. Plant growth measurements at harvest by species. Plants were harvested when they had reached common commercial canopy sizes along with flowers.²

Species	Mean leaf no.	Leaf area (cm ²)	Shoot fresh wt (g)	Root fresh wt (g)	Shoot dry wt (g)	Root dry wt (g)	Water use efficiency ³ (g/L)
<i>Guzmania</i> 'Irene'	33.3 ± 1.2	4,067.4 ± 268.8	176.2 ± 6.9	12.7 ± 2.7	29.1 ± 2.2	2.4 ± 0.4	1.9
<i>Vriesea</i> 'Carly'	28.9 ± 4.2	1,583.5 ± 295.3	48.7 ± 8.7	9.6 ± 1.8	8.5 ± 1.7	2.0 ± 0.4	0.7

²Values represent the means plus SE with four replications except for water use efficiency.

³Water use efficiency is the ratio of total dry weight (g) to total amount of water used (L).

December (day 45). Beginning in Feb. 2007, mean ET_A increased 2.5-fold over the next 50 d to a range from 23.66 to 35.49 mL per day, similar to that shown for *Guzmania* 'Irene' (Fig. 3A). During the summer months of 2007,

mean ET_A averaged around 29.57 mL per day but ranged from 7.5 to 59.89 mL per day during this period. Mean ET_A began declining in August (day 300) to reach a low in Dec. 2007, comparable with that of the first

December and 'Irene'. Mean ET_A again began increasing in late January 2008 to a median mean ET_A of 32.53 mL per day during the summer of 2008. Mean ET_A was variable during this period, ranging from 3.98 mL to 47.32 mL per day. The sharp decline in Aug. 2008 also mirrored that measured the previous year.

Data analysis and modeling. Application of the %CC model (Beeson, 2010a) was successful for both bromeliads with the best fit model presented in Table 2. The significance of r^2 values (0.79 and 0.68 for *Guzmania* and *Vriesea*, respectively) for both equations suggested that the two species exhibited strong relationships between WNI and the level of canopy closure. As derived, equations predict the water use of individual plants. If means could have been derived from these individual plant measurements, such that the relationships were derived for populations of plants, the r^2 would have been higher and predictions of overall crop water use would be more certain.

For both *Guzmania* 'Irene' and *Vriesea* 'Carly', the WNI coefficients declined with increasing plant growth, indicated by the increase in %CC (Fig. 4A and B). In brief, this decline in WNI was due to increases in canopy boundary layer resistance as plant foliage expanded and filled in the gaps between containers. At near 100% canopy closure, transpiration of all but the upper leaves become decoupled from the air above the canopy, resulting in 40% decreases in whole plant transpiration outdoors (Beeson, 2010a). Conversely random removal of $\approx 33\%$ plant canopy coverage had been shown to increase individual plant transpiration by 40% (Beeson, 2010a).

Discussion

Agricultural use of fresh water has been under rigorous scrutiny due to irrigation, accounting for up to 62% of freshwater use, including 68% of groundwater and 29% of surface water withdrawals in the United States (Kenny et al., 2009). Container-grown plant production is an extensive water user within the realm of agriculture (Beeson, 2011; Chen et al., 2001, 2003). Plants are grown in confined volumes filled with artificial substrates, which are watered frequently to avoid drought stress. Irrigation frequency and quantity, however, is largely based on grower's intuition or experience. As a result, plants are often overirrigated (Belayneh et al., 2013). Overirrigation not only reduces substrate aeration but also results in excess runoff and leaching of nutrients, primarily nitrogen (N) and phosphorus (P). Movement of N and P in waterways could potentially

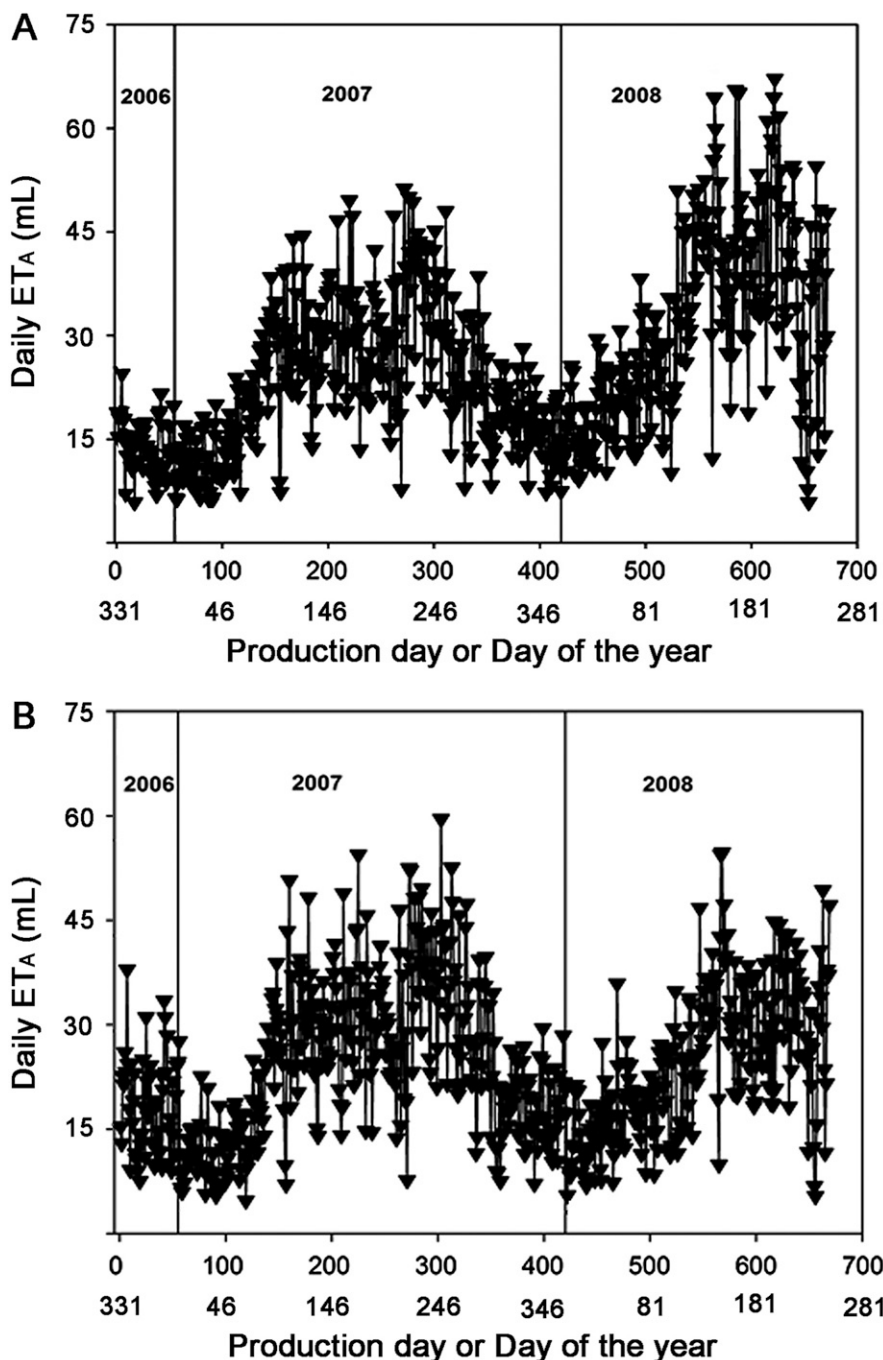


Fig. 3. Mean daily actual evapotranspiration (ET_A) of *Guzmania* 'Irene' (A) and *Vriesea* 'Carly' (B) grown in 15-cm containers during production from tissue-cultured liners to marketable sizes. Each point is the mean of four plant replicates. The horizontal axis is marked with days after transplanting and calendar day.

Table 2. Best-fit models for predicting daily ET_A values of *Guzmania* 'Irene' and *Vriesea* 'Carly' grown in 15-cm containers from tissue-cultured liners to marketable sizes.

Species	Model equation	r^2
<i>Guzmania</i> 'Irene'	$WNI = 0.110 + 0.695/\%CC - 0.132/\%CC^2 - 0.051/\%CC^3$	0.79
<i>Vriesea</i> 'Carly'	$WNI = -3.222 + 5.207/\%CC - 1.685/\%CC^2 - 0.182/\%CC^3$	0.68

ET_A = actual evapotranspiration; r^2 = correlation coefficient; WNI = water need index; %CC = percent canopy closure.

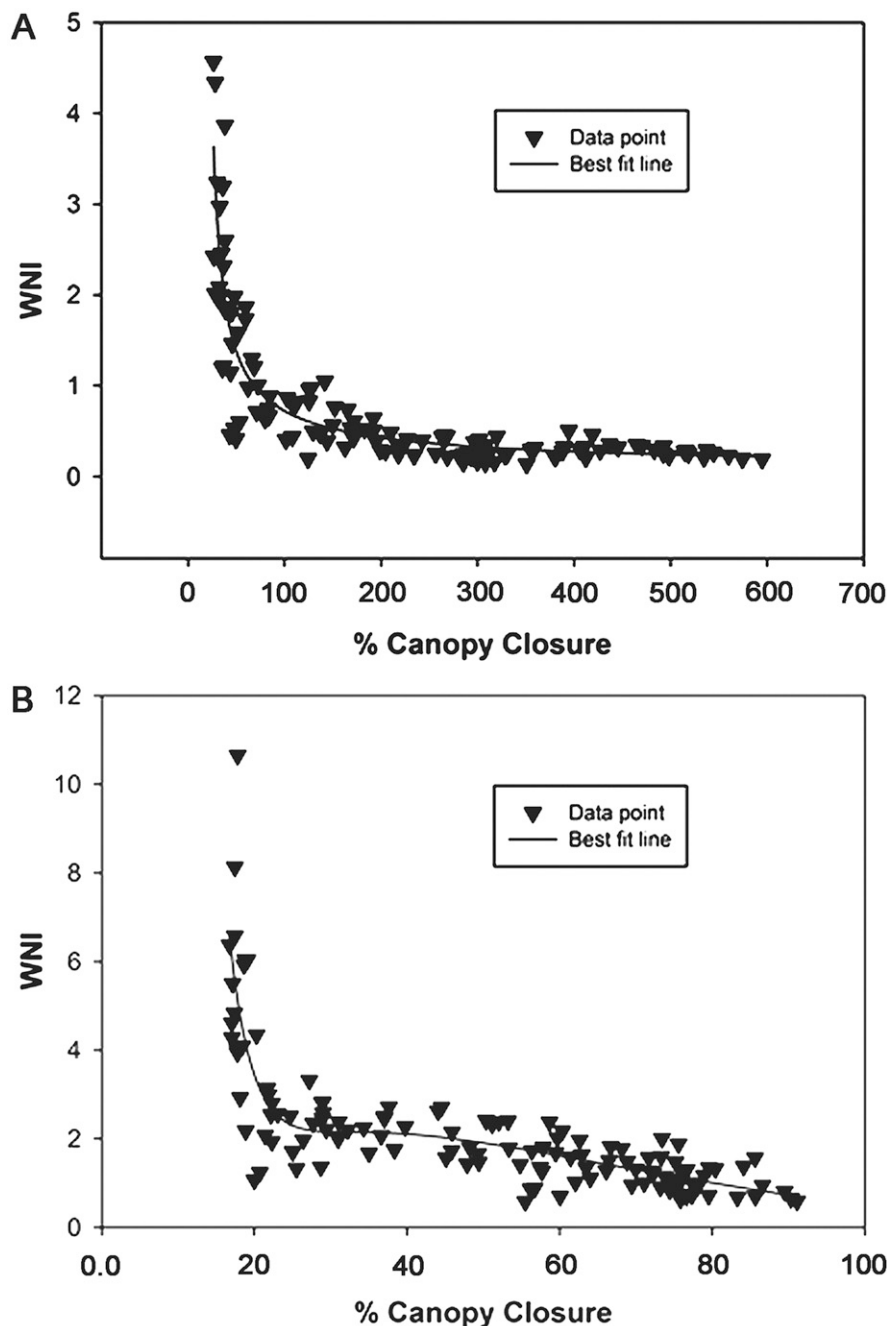


Fig. 4. Inverse polynomial relationship between percent canopy closure (%CC) and the water need index (WNI) for *Guzmania* 'Irene' (A) and *Vriesea* 'Carly' (B). Data points are four plant replicates, and equation for the best-fit line presents in Table 2.

contaminate ground and/or surface water (Chen et al., 2001). Thus, irrigation based on plant growth requirements is increasingly important for sustainable production of container-grown ornamental plants.

The present study shows that plants differ almost daily in water requirements. ET_A values varied from 4.02 to 66.35 mL for *Guzmania* 'Irene' and 3.98 mL to 59.89 mL for *Vriesea* 'Carly' over a 95-week production period. The variation, however, does exhibit an identical pattern regardless of plant species: a slight increase in ET_A in Nov. 2006 that was due to plant establishment after transplanting and then a decrease in the

winter; a substantial increase in early Feb. 2007 and a decrease in late August; and an increase again in late Jan. 2008 and decreased in late August (Fig. 3). The pattern generally coincided with the seasonal changes in Central Florida, suggesting that the growth of these two bromeliads was synchronized by weather conditions, even though they grew in a shaded greenhouse. A difference between the two species is that the daily ET_A values of *Guzmania* from Mar. to Aug. 2008 were much higher than those of *Vriesea*. This could be related to the emergence of bracts of *Guzmania*, where 10 to 15 modified fuchsia-magenta leaves appeared, which

might have much high transpiration than a compact single spike of *Vriesea*.

The cumulative ET_A values of *Guzmania* 'Irene' (16.66 L) and *Vriesea* 'Carly' (15.52 L) were comparable with those our previous studied *Asplenium nidus* (7.95 L) and *Chamaedorea elegans* (6.43 L) (Chen and Beeson, 2013) as well as *Calathea* G. Mey. 'Silhouette' (4.84 L) and *Stromanthe sanguinea* Sond. (6.81 L) (Beeson and Chen, 2018) if considering the production time. The production time for the two bromeliads was 665 d compared with 294 d for both *A. nidus* and *C. elegans*, 224 d for *Calathea*, and 231 d for *Stromanthe*. Commercial production of *Guzmania* and *Vriesea* in 15-cm containers usually takes less than 250 d, during which ethylene is used to force flowering. In our study, we did not use ethylene; plants flowered naturally, which resulted in a prolonged production time. Another note is that *Guzmania* 'Irene' and *Vriesea* 'Carly' varied greatly in leaf areas, shoot, and root dry weights (Table 1), but their cumulative ET_A only differed by 1.1 L. This could be due in part to the faster growth rate of *Guzmania* 'Irene', as illustrated in Fig. 1, and higher water use efficiency (1.9) (Table 1), whereas *Vriesea* 'Carly' growth was slower with a water use efficiency of 0.7. Another reason is that leaves of *Guzmania* 'Irene' were much longer than *Vriesea* 'Carly' (40 cm vs. 16 cm). *Guzmania* 'Irene' reached canopy closure much quicker (Fig. 4A) than *Vriesea* 'Carly' (Fig. 4B). The continuous growth of *Guzmania* 'Irene' caused increased overlapping of leaves, resulting reduced transpiration and the demand for water, as shown in Fig. 4A. In contrast, the appearance of 10 to 15 bracts after May 2008 increased transpiration; thus, ET_A of *Guzmania* 'Irene' was higher compared with *Vriesea* 'Carly' during the same period. Nevertheless, the application of the canopy closure model was successful for both bromeliads, and the best-fit model is presented in Table 2. The r^2 values for the WNI as a function of %CC were high, 0.79 for *Guzmania* 'Irene' and 0.68 for *Vriesea* 'Carly'. Results from this study, along with the previous reports (Beeson and Chen, 2018; Chen and Beeson, 2013) suggest that the canopy closure model and WNI developed for woody ornamental plants are suitable for modeling daily water requirements of container-grown foliage plants in greenhouse conditions. As far as we know, this is the first report on the daily water use of bromeliads. This study provides important information for commercial production of both *Guzmania* and *Vriesea* and probably other bromeliads.

This study also showed that roots of both *Guzmania* 'Irene' and *Vriesea* 'Carly' were functional. Since plants were fertilized by topdressing a CRF on substrate and watered via drip irrigation and not through tank, water and nutrients must have been taken up through roots. As shown in Fig. 1, both *Guzmania* 'Irene' and *Vriesea* 'Carly' indeed had well-developed root systems. Interestingly, root systems of many tank bromeliads, such as Tillandsioideae species in general, often are classified as nonabsorptive and mainly serving

to anchor these plants (Benzing, 2000), whereas foliar trichomes are essential for water and nutrient absorption from the tank solution (Inselsbacher et al., 2007). Our results showed that epiphytic bromeliads, when cultivated in a substrate, emitted new roots that are functional. Vanhoutte et al. (2017) also showed that roots of *Vriesea* are important for water and nutrient absorption. The importance of trichomes in water and nutrient absorption could be due to the evolutionary adaptation of epiphytic bromeliads in the wild. The ability of cultivated bromeliad roots to take up water and nutrients may suggest great physiological plasticity of epiphytic bromeliads in adaptation to commercial cultivation. Breeding of bromeliads for ornamental purposes also may select plant roots not only for anchoring plants but also for effective absorption of water and nutrient for commercial production.

In conclusion, the canopy closure model and WNI developed for woody ornamental plants are suitable for modeling daily water requirements of container-grown foliage plants in greenhouse conditions. The daily ET_A established for *Guzmania* and *Vriesea* could be used as references for developing optimal irrigation recommendations for commercial bromeliad production. Development of WNI models for other groups of bromeliads would like conserve water and reduce nutrient leaching. In addition, *Guzmania* and *Vriesea* develop functional roots and can be irrigated via roots or roots and tanks in commercial bromeliad production.

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