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Quantification of Daily Water Requirements of Container-Grown *Calathea* and *Stromanthe* Produced in a Shaded Greenhouse

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Abstract: Irrigating plants based on their water requirements enhances water use efficiency and conservation; however, current irrigation practices for container-grown greenhouse plants largely relies on growers' experiences, resulting in leaching and/or runoff of a large amount of water. To address water requirements of greenhouse-grown plants, this study adapted a canopy closure model and investigated actual evapotranspiration (ET_A) of *Calathea* G. Mey. 'Silhouette' and *Stromanthe sanguinea* Sond. from transplanting to marketable sizes in a shaded greenhouse. The daily ET_A per *Calathea* plant ranged from 3.55 mL to 59.39 mL with a mean cumulative ET_A of 4.84 L during a 224 day growth period. The daily ET_A of *S. sanguinea* varied from 7.87 mL to 97.27 mL per plant with a mean cumulative ET_A of 6.81 L over a 231 day production period. The best fit models for predicting daily ET_A of *Calathea* and *Stromanthe* were developed, which had correlation coefficients (r^2) of 0.82 and 0.73, respectively. The success in modelling ET_A of the two species suggested that the canopy closure model was suitable for quantifying water use of container-grown greenhouse plants. Applying the research-based ET_A information in production could reduce water use and improve irrigation efficiency during *Calathea* and *Stromanthe* production.

Keywords: actual evapotranspiration (ET_A); *Calathea*; container-grown plants; daily water requirements; ornamental foliage plants; *Stromanthe*; water need index (WNI)

1. Introduction

Freshwater is one of our most precious natural resources. Agricultural use of freshwater has been under rigorous scrutiny since irrigation withdrawals represent over 70% of all freshwater use worldwide [1,2]. In the United States (U.S.), irrigation accounts for 68% of groundwater and 29% of surface water withdrawals, encompassing up to 62% of all freshwater use [3]. Container plant production is an important sector of agriculture, which refers to growing plants from seedlings, liners, rooted cuttings, or grafted plants in containers or pots filled with substrates to marketable sizes or harvestable stages [4]. Growing media or substrates consist of a mix of soil, peat, vermiculate, perlite, or other organic components in different proportions. Container production is a widely-utilized method for growing a variety of plants including fruit, vegetable, nursery, and floriculture crops. Floriculture and nursery crops comprise almost 30% of the specialty crops grown in the U.S. with a total of \$11.7 billion in sales in 2009 [5]. Container production in the U.S. currently accounts for approximately 90% of greenhouse, nursery, and floriculture crops [6]. Since plants are grown in artificial substrates confined by limited volumes (containers), they have to be frequently irrigated ranging from daily to weekly to avoid drought stress. Current irrigation practices have been largely based on growers' intuition or experience, and as a result, plants are often overirrigated [7]. Overirrigation has been

reported to result in 25% to 90% of irrigated water to be leached and/or runoff [8–11]. Overirrigation not only reduces substrate aeration but also results in irrigation leaching and/or runoff, which is accompanied with nutrient elements, primarily nitrogen (N) and phosphorus (P). The movement of N and P in waterways could potentially contaminate ground and/or surface water [8]. Thus, irrigation based on plant growth requirements is becoming increasingly important for sustainable production of container-grown plants.

Plant water use is mainly a function of transpiration through leaves. When evaporation from soil or other substrates is included, water use is termed actual evapotranspiration (ET_A , mL day⁻¹). Transpiration accounts for the majority of actual ET_A , but it can be affected by local weather conditions, cropping system, plant species, and growth stages [12]. As a result, ET_A is estimated by multiplying reference ET (ET_0 , mL day⁻¹) with a corresponding crop coefficient (K_c , dimensionless) [12]. The Penman–Monteith equation has been recommended as the sole method of estimating ET_0 [12], which is calculated by multiplying weather-based estimates of ET from a reference crop, such as grass or alfalfa. There are several modifications to the Penman–Monteith model that provide the same values for ET_0 . One is the grass reference option established by the American Society of Civil Engineering (ASCE) [13]. Another is the program provided by Campbell Scientific Inc. (Logan, UT, USA) for its weather stations [14] that uses the full ASCE Penman–Monteith equation [15]. K_c is a function of fraction of ground cover and crop height, and K_c values have been reported for a wide range of agronomic crops [12,16]. However, accurate K_c values are difficult and expensive to develop [17]. Using precision weighing lysimeters is the most accurate way of estimating crop water usage and developing K_c . Weighing lysimeters have generally been regarded as the standard measuring device for estimating ET; they do so by measuring changes in mass of a soil container with plants positioned on a scale or other weight device. Weighing lysimeters measure ET_A as volumes, rather than depths.

Quantification of daily water use of container-grown plants dates back to the 1980s. The Thornthwaite equation [18] was the original method used [19,20] to calculate ET_0 . Other researchers used the top diameter of container [21] for calculating the surface area to convert ET_A to a depth for 22 woody ornamental species, and K_c values ranging from 1.1 to 5.1 were reported. In agronomic crops, however, K_c values rarely exceed 1.3 [22]. This represents a major discrepancy between agronomic and container plants. Agronomic crops are produced in the field, and ET_A and K_c are estimated in reference to an irrigated area or a ground area, which includes ground cover and canopy. In container-grown plants, ET_A is mostly measured by weight loss from a container initially near 100% container capacity; as such, ET_A is a measure in volume. However, ET_0 is calculated as a depth (mL). In container plant production, projected canopy areas (PCA) generally exceed container surfaces by several times. Evapotranspiration, mainly transpiration, takes place throughout the canopy. Since the measure of ET_A is in volume, it has to be normalized by an area to be the same units as ET_0 for the calculation of K_c . An approach to normalized ET_A is to calculate it based on PCA. When ET_A was normalized by both ET_0 and PCA, K_c declined as PCA approached canopy closure and became relatively constant after canopy closure [23]. Thus, it was proposed that the calculation of K_c of container-grown plants was based on canopy closure [24]. When using this model, researchers determine average canopy area and calculates percent canopy closure (%CC) based on distance between adjacent containers and the canopies of similar plants. Based on the ET_A , ET_0 , and PCA, a water needs index (WNI) is calculated, which is a function of canopy closure of a group of plants, relating individual plant actual evapotranspiration (ET_A) to plant size and canopy ventilation and radiation [25]. Daily ET_0 was calculated from a meteorological measurement on site, with ET_A determined by an autonomous weighing lysimeter system [10]. The model has been used to quantify daily ET_A of several woody ornamental plants to market size including *Ligustrum japonicum* Thunb. [24], *Viburnum odoratissimum* Ker Gawl. [26,27], *Rhaphiolepis indica* (L.) Lindl. ex Her Gawl. [28] as well as foliage plants of *Asplenium nidus* L. and *Chamaedorea elegans* Mart. [29]. The irrigation of container plants based on daily water use has been documented to reduce nursery runoff volume and nutrient load without reducing plant growth [30,31].

The objectives of the present study were to determine ET_A of two important container-grown ornamental foliage plants, *Calathea* G. Mey. 'Silhouette' and *Stromanthe sanguinea* Sond., in a shaded greenhouse from tissue-cultured liners grown in 15 cm containers to marketable sizes, and to develop models to predict daily ET_A rates using the PCA model developed for container-grown woody ornamental plants. Foliage plants are those produced in shaded greenhouses and used primarily for interior decoration [32]. Florida is the leading state in the production of foliage plants, accounting for 72% of wholesale value in the U.S. in 2015 [33]. Quantification of their daily water use could provide research-based information for improving irrigation efficiency during foliage plant production in greenhouse conditions.

2. Materials and Methods

2.1. Experimental Location

The experiment was conducted in a shaded greenhouse at the University of Florida's Mid-Florida Research and Education Center (MREC) in Apopka where a Florida Automated Weather Network (FAWN) station was 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), dew point, rainfall, soil temperature, relative humidity, wet bulb temperature, barometric pressure, and wind speed every 15 min daily as well as daily evapotranspiration (ET).

2.2. Experimental Setup

An automated Weatherhawk weather station (Campbell Scientific Inc., Logan, UT, USA) was installed inside the shaded greenhouse where a miniature weighing lysimeter system was built for this study [10]. In brief, the system consisted of a control/data collection apparatus connected to mini lysimeters where a SDM-AM16-32 multiplexer (Campbell Scientific Inc., Logan, UT, USA), a CR10X data logger (Campbell Scientific Inc., Logan, UT, USA), and SDM-CD16AC relay control module (Campbell Scientific Inc., Logan, UT, USA) were used for receiving and storing data from the mini-lysimeters. Each mini-lysimeter was installed with a load cell (SSM-50-AJ, Interface Inc., Scottsdale, AZ, USA) that was suspended from a miniature tripod with a plant support. All load cells were calibrated with a seven-point curve using known masses. Every half hour, the data logger program recorded the mass of each lysimeter and stored it for later retrieval. At midnight, actual evapotranspiration (ET_A) for each lysimeter was determined as the difference in mass between 0500 h and midnight. There was no transpiration between midnight and 0500 h.

2.3. Plant Materials and Their Growth

Tissue-cultured liners (plantlets grown in plugs of 72 cell trays) of *Calathea* 'Silhouette' and *S. sanguinea* were transplanted singly into a peat-based substrate composed of 60% Canadian peat, 20% vermiculite, and 20% perlite in 15 cm containers. *Stromanthe* plants were transplanted on 8 September 2008 and harvested on 23 April 2009; and *Calathea* plants were transplanted on 7 July 2009 and harvested on 18 February 2010. Plants were fertilized by top dressing 5 g of a controlled-released fertilizer (CRF) (Osmocote 19–5–9, 8–9 month, The Scotts Co., Marysville, OH, USA) per container three weeks after potting. The experiment was arranged as a completely randomized block design with four replications. Each block had 15 plants per species, they were spaced in three rows, five containers along the length of benches, 30 cm apart. The center plant was placed in a suspension-weighing lysimeter, and the four closest plants to the lysimeter plant were designated as the interior plants for repeated canopy measurements. Plants were produced in the aforementioned shaded greenhouse under a maximum photosynthetic active radiation (PAR) of $200 \mu\text{mol m}^{-2} \text{s}^{-1}$.

Plants were irrigated between 0800 h and 0900 h and allowed to have about 10% leachate fraction. Irrigation was supplied through self-fashioned rings of pressure-compensated drip tubing (Netafilm, Fresno, CA, USA). Pressure-compensating emitters were made in 30.5 cm intervals along the length of

the tubing. There were four emitters that were cut and rolled to form two loops joined by a T-barb. Each container had a joined loop which was connected to 19 mm polyethylene tubing using equal lengths of 6 mm tubing. Water application for 15 loops (15 plants) was calculated by Christensen's coefficients of uniformity 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 per minute.

2.4. Data Collection

Greenhouse air temperature, relative humidity, wind speed, and solar radiation required for calculation of reference evapotranspiration (ET_0) was collected from the automated Weatherhawk weather station. The algorithm used for calculating reference evapotranspiration (ET_0) was based on the Campbell Scientific program.

Plant growth data were collected a week after potting. The widest width, width perpendicular to the widest width, and average height of the canopy were measured every three weeks on the lysimeter plants and adjacent four interior plants of each replication. The two widths were multiplied to estimate the two-dimensional PCA. When PCA was multiplied by the average height, canopy volume or growth index (GI) was estimated [34,35], assuming the three-dimensional canopy resembled a rectangular form. Plant water-use efficiency was calculated as total dry matter produced (g) by actual amount of water used (ET_A) [36].

2.5. Modelling Plant Water Use

The %CC, ET_A , ET_0 , and PCA [24,26,27] were utilized for modelling the daily water use of two plant species. The %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). This was the squared distance, at the center, between each plant. Since the containers were not respaced, canopies could become overlapped as shoots per plant expanded outward and up. The overlapping could result in calculation of %CC greater than 100% since it was determined on a fixed allocated bed area.

Daily ET_A (cm³) of each lysimeter plant was converted to a depth by dividing with its PCA (cm²). ET_A depth (cm) was then divided by the corresponding ET_0 (cm) and averaged over the seven days to calculate WNI [$WNI = (ET_A/PCA)/ET_0$] [28] for each lysimeter plant at each measurement date. Obtained 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 (Version10; SPSS Inc., Chicago, IL, USA). The plot was also fitted to a third-order inverse polynomial equation also using SigmaPlot. An equation for the nonlinear line was derived using a three-level inverse polynomial equation (Version10; SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Reference Evapotranspiration

The ET derived from FAWN from September 2008 to April 2009 ranged from 1.02 to 4.83 mm with a mean of 2.36 mm. The ET from July 2009 to February 2010 varied from 1.02 to 5.58 mm with a mean of 2.75 mm. The ET_0 values in the shaded greenhouse were about 12% of that outside the shaded greenhouse as measured by the FAWN station during the mentioned time. Relative humidity was normally higher, more than 75% inside the greenhouse. Air movement happened during most afternoons from early-Spring until late Fall due to the operation of evaporative cooling fans, although there was no measurable wind movement. 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_0 was highest in April and May (days 90 to 150), then declined the rest of the period with the onset of summer rains, then shorter days.

3.2. Plant Growth

Canopy height and widths of *Calathea* ‘Silhouette’ increased in a polynomial fashion (data not shown). Growth index also increased polynomially (Figure 1A). *Calathea* ‘Silhouette’ at the time of harvest produced 19.4 leaves with a total leaf area of 852 cm². Shoot and root fresh weights were 33.8 and 5.6 g; and shoot and root dry weights were 3.7 and 0.5 g, respectively (Table 1).

Canopy heights and widths of *S. sanguinea* increased linearly over the production time (data not shown), but canopy width and growth index increased polynomially (Figure 1B). At harvest, the mean number of leaves was 84 with a total leaf area of 2729.2 cm². Shoot and root fresh weights were 110.7 and 42.2 g, and corresponding dry weights were 14.4 and 3.0 g, respectively (Table 1).

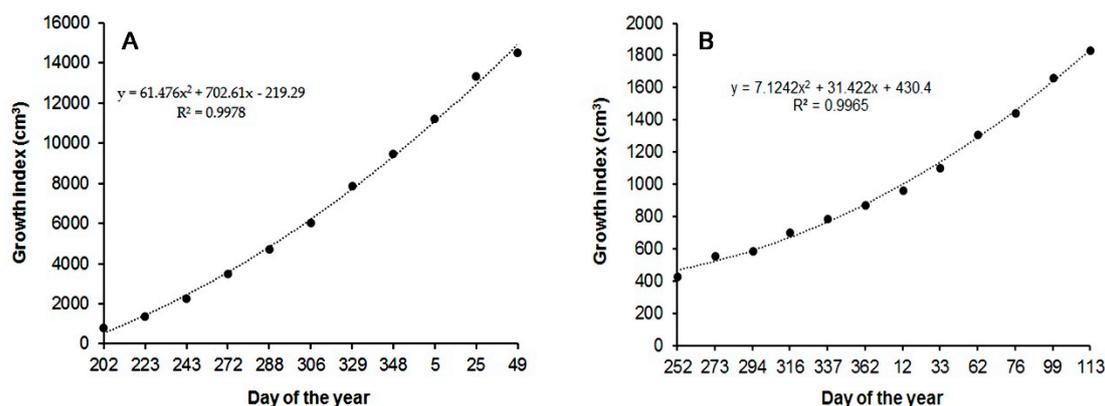


Figure 1. Growth indices (cm³) of *Calathea* ‘Silhouette’ (A) and *Stromanthe sanguinea* (B) grown in 15 cm containers from tissue-cultured liners to marketable sizes. The equations are the best fit line (dash).

Table 1. Plant growth measurements at harvest by species. Plants were harvested when common commercial canopy sizes were attained ^z.

Plant	Mean Leaf No	Leaf Area (cm ²)	Shoot Fresh Weight (g)	Root Fresh Weight (g)	Shoot Dry Weight (g)	Root Dry Weight (g)	Water Use Efficiency (g L ⁻¹) ^y
<i>Calathea</i>	19.4 ± 0.59	852.0 ± 54.60	33.8 ± 2.40	5.6 ± 0.37	3.7 ± 0.33	0.5 ± 0.04	0.87
<i>Stromanthe</i>	84.0 ± 2.49	2729.2 ± 68.36	110.7 ± 3.10	42.2 ± 1.35	14.4 ± 0.17	3.0 ± 0.08	2.56

^z Values represent the means ± standard errors of four replications. ^y Water use efficiency = the ratio of total dry weight (g) to total amount of water used (L).

3.3. Plant Actual Evapotranspiration (ET_A)

Daily ET_A per *Calathea* ‘Silhouette’ plant ranged from 3.55 mL to 59.39 mL (Figure 2A) with an overall mean of 21.6 mL a day per plant. The mean cumulative ET_A was 4.84 L over a 224 day production period that span mid-summer 2009 to mid-February 2010. Corresponding to the beginning of production in mid-summer and finishing in late winter, mean ET_A was initially higher, up to 59.39 mL, then declined through the production period. By late October (day 120), mean ET_A stopped declining, ranging generally from 11.83 to 23.66 mL per day until harvest.

Daily ET_A for producing *S. sanguinea* ranged from 7.87 to 97.27 mL with a mean of 29.5 mL (Figure 2B). The mean cumulative ET_A value was 6.81 L per plant during the entire production period. Mean daily ET_A declined from transplanting through the end of the year. Mean ET_A during this period decreased from 36.97 mL to 17.74 mL per day. Increases in mean ET_A were slow to occur until early March 2009, when daily ET_A increased from around 29.57 mL per day to a median of 73.93 mL per day over a 20 day period. The increase in mean daily ET_A occurred due to large increases in daily variability. With the weeks before harvest, mean daily ET_A ranged from 14.79 mL to nearly 97.27 mL per day.

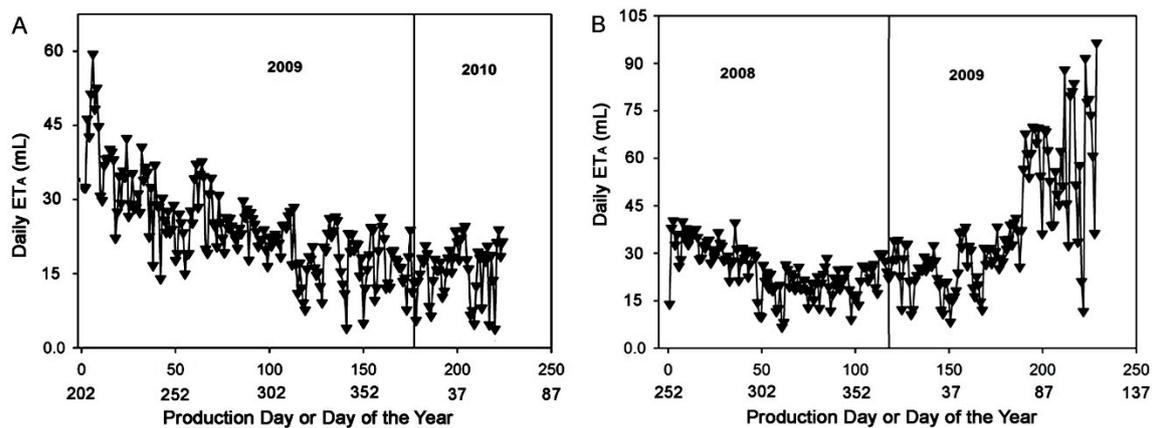


Figure 2. Mean daily actual evapotranspiration (ET_A) of *Calathea 'Silhouette'* (A) and *Stromanthe sanguinea* (B) grown in 15 cm containers during production from tissue-cultured liners to marketable sizes. Each triangle is the mean daily ET_A of four plant replicates. The vertical line separates the year.

3.4. Data Analysis and Modeling

Application of the %CC model [26] was successful for both *Calathea* and *Stromanthe* with the best fit model presented in Table 2. The r^2 values were 0.82 and 0.73 for *Calathea* and *Stromanthe*, respectively, suggesting that strong correlations occurred between WNI and %CC for the two species. The equations predicted 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 be even higher and predictions of overall crop water use would be more certain. The WNI coefficients declined as both plants' growth increased, which was illustrated by the increase in %CC (Figure 3A,B). The decline in WNI was due to the increase in canopy boundary layer resistance as plant foliage expanded and filled in the gaps between containers. When reaching near 100% CC, transpiration of all but the upper leaves become decoupled from the air above the canopy, resulting in 40% decreases in whole plant transpiration outdoors [26]. Conversely, random removal of approximately 33% plant canopy coverage has been shown to increase individual plant transpiration by 40% [26].

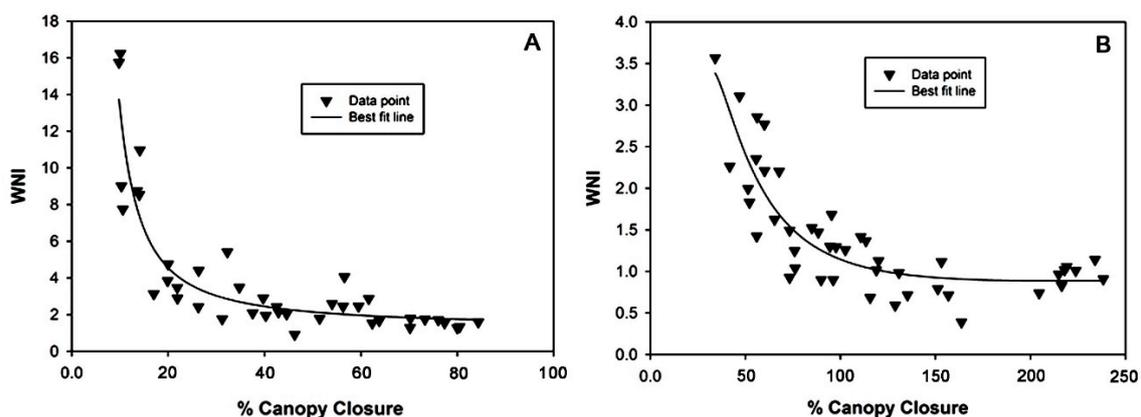


Figure 3. Inverse polynomial relationship between % Canopy Closure (CC) and the water need index (WNI) for *Calathea 'Silhouette'* (A) and *Stromanthe sanguinea* (B). Data points are four plant replicates, and the equation for the best fit line is present in Table 2.

Table 2. Best fit models for predicting daily ET_A values of *Calathea* ‘Silhouette’ and *Stromanthe sanguinea* during production from tissue-cultured liners to marketable sizes in 15 cm containers.

Species	Model Equation	r^2
<i>Calathea</i>	$WNI = 1.213 + 0.383/\%CC + 0.032/(\%CC)^2 + 0.005/(\%CC)^3$	0.82
<i>Stromanthe</i>	$WNI = 1.136 - 1.131/\%CC + 1.395/(\%CC)^2 - 0.255/(\%CC)^3$	0.73

4. Discussion

The present study investigated daily ET_A of two important container-grown ornamental foliage plants, *Calathea* ‘Silhouette’ and *S. sanguinea*, from tissue-cultured liners to marketable sizes in a shaded greenhouse. Results showed that daily water requirements of *Calathea* varied from 3.55 mL to 59.39 mL over a 224 day production period, and the cumulative ET_A for producing this plant was 4.84 L. The daily water requirements of *S. sanguinea* ranged from 7.87 mL to 97.27 mL and its cumulative ET_A was 6.81 L. The cumulative ET_A values were comparable to two other container-grown foliage plants, *A. nidus* and *C. elegans* [29], in which both were grown in 15 cm containers with cumulative ET_A values of 7.95 L for *A. nidus* during a 294 day growth and 6.43 L for *C. elegans* during a 280 day production period. Although there has been little ET_A information available about container plants produced in greenhouse conditions, we believe that the cumulative ET_A data were valid. Researchers have produced foliage plants *Codiaeum variegatum* ‘Petra’, *Dieffenbachia maculate* ‘Camelle’, and *Spathiphyllum* ‘Petite’ in 15 cm containers in an ebb-and-flow system from cuttings or tissue-cultured liners to marketable size [37]. Ebb-and-flow is a system where container plants on ebb-and-flow trays are subirrigated with recirculated nutrient solution. There is no irrigation water runoff, and the amount of water lost during the production can be quantified. The authors reported that the total amount of water used by the plants ranged from 6.8 L to 7.9 L depending on nitrogen rates. The same ebb-and-flow system has been used to produce 18 foliage plants across 15 genera in 15 cm containers in a shaded greenhouse and it has been found that the average amount of water required for producing these plants from cuttings or tissue culture liners to marketable sizes was 10.22 L [9]. The calculated amount of water loss on ebb-and-flow systems could be greater than those produced in the present study. This is because each ebb-and-flow tray has a surface area of 2.4 m², and water or nutrient solution are flooded in the trays to a depth of 2.5 cm for 10 min one to three times a week, during which a certain amount of water was lost due to evaporation.

Results from this study showed that the canopy closure model and WNI developed for woody ornamental plants are suitable for modelling daily water requirements of container-grown foliage plants in greenhouse conditions. In the present study, canopy widths and height were recorded every three weeks, and PCA and %CC were calculated based on container size and spacing. Using %CC, Kc values were calculated. The Kc values were multiplied by PCA and ET_0 to estimate the ET_A on daily base. WNI was then calculated by the formula $(ET_A/PCA)/ET_0$ [28]. The plots of WNI as a function of %CC for both *Calathea* and *Stromanthe* (Figure 3A,B) were fitted to the equations presented in Table 2 with the correlation coefficients (r^2) 0.82 and 0.73 for *Calathea* and *Stromanthe*, respectively. The modelling ET_A based on the aforementioned method has several advantages [25]. Kc calculation is based on canopy closure, it should be independent from container size. It also should avoid the need to use Fourier curve transformations to account for changes in ET_A or growth with season. Development of models based on canopy components should be easier to convert to predictive irrigation models than those that require complex transformation or provide Kc range only. On the other hand, if the %CC or PCA does not change, neither should the relationship of ET_A to ET_0 , suggesting a period of canopy dormancy.

As far as is known, this is the first report on daily water use for *Calathea* and *Stromanthe*. This information along with ET_A values estimated in another two foliage plants, *Asplenium* and *Chamaedorea*, showed that foliage plants have rather lower cumulative ET_A values than other ornamental plants grown in greenhouses. For example, cumulative water use of two *Petunia hybrida*

cultivars were 2.71 L and 4.08 L, respectively, when they were produced in 15 cm containers for 46 days [38]. The lower ET_A is likely related to the natural habits of their origin. Foliage plants were predominantly understory plants [39]; their leaves have thicker cuticles; the plants require lower light levels and lower nutrient input for growth. As a result, their net photosynthetic and transpiration rates are lower [40]. Commercial production of foliage plants, however, has not fully considered these characteristics. Traditional overhead irrigation resulted in the runoff of 90% of irrigation water. Subsequent improvement on irrigation with a capillary mat used 19 L to 23 L of irrigation water per plant, and drip irrigation used 10 L to 12 L of water [41]. Compared to the cumulative ET_A values ranging from 4.82 L to 7.95 L with those from either drip or capillary mat irrigation, irrigation of plants based ET_A could substantially save freshwater in container-grown foliage plant production. Plants from more than 1000 species across more than 100 genera are grown as ornamental foliage plants [32], and water requirements and water use efficiency could vary among species. For example, the water use efficiency of *Stromanthe* is three times greater than that of *Calathea* (Table 1). To irrigate container-grown foliage plants based on their requirements, the ET_A of each genus should be determined. The methodologies presented in this study provide an easy and affordable way to quantify daily water use, and the application of ET_A information into irrigation practices should significantly improve irrigation efficiency and conserve freshwater resources.

5. Conclusions

The daily ET_A established for *Calathea* and *Stromanthe* as well as those previously established for *A. nidus* and *C. elegans* suggest that the canopy closure model and WNI developed for woody ornamental plants are suitable for modelling daily water requirements of container-grown foliage plants produced in greenhouse conditions. The daily ET_A established for *Calathea* and *Stromanthe* could be used as reference guidelines for improving irrigation practices in commercial production of foliage plants. The application of ET_A should significantly reduce irrigation water runoff and leaching and conserve freshwater resources.

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