A Calibrated Time Domain Transmissometry Soil Moisture Sensor Can Be Used for Precise Automated Irrigation of Container-grown Plants

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Abstract. Irrigation control systems that irrigate container-grown plants based on crop water needs can reduce water and fertilizer use and increase the sustainability of ornamental crop production. The use of soil moisture sensors to determine when to irrigate is a viable option. We tested a commercially available irrigation controller (CS3500; Acclima, Meridian, ID), which uses time domain transmissometry (TDT) sensors to measure soil volumetric water content (θ). The objectives of this study were: 1) to test the accuracy of TDT sensors in soilless substrate; 2) to quantify the ability of the Acclima CS3500 irrigation controller to maintain stable θ readings during the production of container-grown begonia (*Begonia semperflorens* L.) by turning a drip irrigation system on and off as needed; and 3) to study the growth and photosynthetic physiology of begonia at six θ levels. Calibration of the TDT sensors in pots filled with substrate (but without plants) showed that the θ determined by the TDT sensors had a very close relationship ($R^2 = 0.99$) with the gravimetrically determined θ , but the TDT sensors underestimated θ by $\approx 0.08 \text{ m}^3 \cdot \text{m}^{-3}$. Therefore, a custom calibration of the TDT sensors for the soilless substrate was necessary to get accurate θ data. The irrigation controller was programmed to maintain six θ thresholds, ranging from 0.136 to 0.472 $\text{m}^3 \cdot \text{m}^{-3}$ (based on our own sensor calibration), and was able to maintain θ readings within 0.008 $\text{m}^3 \cdot \text{m}^{-3}$ of the threshold. Theta and Sigma probes were used to collect comparative θ and bulk electrical conductivity (EC) data, respectively. The results showed a strong correlation with TDT sensor measurements of θ ($R^2 = 0.92$) but a moderate relationship for bulk EC ($R^2 = 0.53$). The begonias had similar dry weight at θ levels of 0.348 $\text{m}^3 \cdot \text{m}^{-3}$ and higher, whereas total evapotranspiration increased linearly with the θ threshold. The lowest θ threshold reduced leaf size, net photosynthesis (P_n), and stomatal conductance (g_s). Overall, the TDT sensors can provide accurate measurements of θ in soilless substrate but need substrate-specific calibration. The Acclima CS3500 controller, using TDT sensors, was able to maintain stable θ readings throughout a production cycle. These results suggest that this irrigation controller may be suitable for production of greenhouse crops as well as in drought stress research.

Water conservation through more efficient irrigation has received much attention in recent years, especially in regions suffering from drought and with limited water availability. Population growth and increased urbanization have increased competition for water (Jury and

Vaux, 2005). Furthermore, consumers and governments are increasingly interested in agricultural sustainability, resulting in market opportunities for sustainable ornamental crops (Dennis et al., 2010). The ornamentals industry will also need to comply with existing and new laws, regulating the environmental impact of production (Fernandez et al., 2009). Sustainable ornamental crop production must include appropriate irrigation practices. Excessive irrigation results in leaching and runoff of water and fertilizer, which may cause eutrophication and algal blooms (Conover and Poole, 1992; Majsztrik et al., 2011). More efficient irrigation practices can also reduce energy use and CO₂ emissions.

To achieve more efficient irrigation, growers should not use timers or make irrigation

decisions based on the visual appearance of the substrate or plants (Nemali et al., 2007). Instead, environmental measurements such as evapotranspiration (Allen et al., 1998) and soil or substrate θ or tension (Shock and Wang, 2011; Toop and Ferre, 2002) can be used to infer plant water needs and to schedule agricultural, municipal, or residential irrigation (Blonquist et al., 2006). Measurements of θ are particularly useful for precise irrigation scheduling in uniform nursery container mixes (Shock and Wang, 2011). Jones (2007) concluded that soil θ is the most valuable environmental or plant variable for irrigation control, allowing for easy automation. Automating irrigation based on soil water tension has been used for decades (see Shock and Wang, 2011), whereas the use of soil or substrate θ has become more feasible in recent years with the advent of low-cost sensors (e.g., Nemali and van Iersel, 2006).

Nemali and van Iersel (2006) developed an automated irrigation system that can maintain substrate θ at specific thresholds. The system was accurate and successfully used in further work to study irrigation efficiency in gaura (*Gaura lindheimeri* Engelm. & Gray ‘Siskiyou Pink’) (Burnett and van Iersel, 2008) and petunia (*Petunia $\times$ hybrida*) (van Iersel et al., 2010). This irrigation system determines θ with capacitance sensors connected to a datalogger. The datalogger can control irrigation by opening and closing solenoid valves as needed. The limitation of this system is that a basic knowledge of programming and wiring dataloggers is required. However, there are commercially available irrigation systems that not only include soil moisture sensors, but also an interface to control irrigation. Cardenas-Lailhacar and Dukes (2010) tested four commercial, sensor-based irrigation systems in a coarse-textured soil (Arredondo fine sand) and concluded that TDT sensors (Acclima) could be used for accurate control of θ in field plots with Bermuda grass [*Cynodon dactylon* (L.) Pers.]. McCready et al. (2009) tested the same TDT sensor in a similar soil (field capacity $\approx 11\%$) but with three different θ levels (7% dry, 10% medium, and 13% wet) and showed that θ levels of 7% and 10% reduce water use, although 7% reduced St. Augustine grass [*Stenotaphrum secundatum* (Walter) Kuntze] quality.

The TDT sensor measures the permittivity of the soil by sending an electromagnetic signal along a waveguide and measuring the propagation time of that wave. This propagation time depends on the soil dielectric properties, which are mainly governed by the water content of the soil surrounding the probes (Blonquist et al., 2005a). The TDT sensor provides accurate apparent permittivity measurements, which can be used to estimate θ (Blonquist et al., 2005a). The distortion parameters of the returned wave are used to determine the bulk EC. The dimensions of the TDT sensor are 20.3 cm $\times$ 5.4 cm $\times$ 1.4 cm (length $\times$ width $\times$ height) and they explore $\approx 200 \text{ mL}$ of soil or substrate (Blonquist et al., 2006). These sensors have potential use in the irrigation of ornamental crops as well as

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irrigation and drought stress research. However, TDT sensors may need a specific calibration for soilless substrate, because the dielectric properties differ from those of mineral soil for which the standard factory calibration was developed. Using TDT sensors with an irrigation controller (e.g., CS3500; Acclima) can provide similar information as the automated irrigation system described by Nemali and van Iersel (2006). To assess the potential of such irrigation control for use with container-grown plants, the accuracy and performance of the sensors, controller, and irrigation system need to be tested. Thus, the aims of this study were: 1) to evaluate the built-in calibration of TDT sensors in soilless substrate and their accuracy in determining θ ; 2) to quantify the ability of the Acclima CS3500 irrigation controller to maintain stable θ readings during the production of container-grown begonia (*Begonia semperflorans* L.) by turning a drip irrigation system on and off as needed; and 3) to study the growth and photosynthetic physiology of begonias at six θ levels.

Material and Methods

Sensor calibration. The TDT sensors were calibrated following the protocol described by Nemali et al. (2007). Briefly, different amounts of water were mixed into 3.65 L of substrate (45% peatmoss, 15% perlite, 15% vermiculite, and 25% bark; Fafard 3B; Fafard, Agawam, MA) and pots were filled with this substrate. The sensors were inserted into the substrate while carefully maintaining close contact between the substrate and TDT sensor by slightly compressing the substrate. The TDT sensors were connected to an irrigation controller (CS3500; Acclima), which was used to take sensor readings. These readings provided measurements of θ using the standard soil calibration built into the irrigation controller software (Irrigation Manager; Acclima). The pots with substrate were then weighed, oven-dried at 60 °C until constant weight was reached, and θ was determined as $[(SW_1 - SW_2)/V]$, where SW_1 is the substrate weight before drying, SW_2 the substrate weight after drying, and V the volume of the pot. The accuracy of the sensors was evaluated by plotting the θ as measured by the irrigation controller versus the θ determined from substrate weight and volume.

Plant material and crop conditions. Begonia seedlings were obtained from a commercial seedling producer (Speedling, Blairsville, GA). The seedlings were transplanted into 19.5-cm diameter, round pots with a 3.65-L volume filled with a soilless substrate (Fafard 3B; Fafard) and amended with a slow-release fertilizer (Osmocote Plus 14-14-14; 14N-4.2P-11.6K; The Scotts Co., Marysville, OH) at a rate of 15 g/pot.

Pots were arranged in 12 rows of five plants and irrigation of each row of plants was controlled using a 2.5-cm solenoid valve (Watermaster; Orbit Irrigation Products, Bountiful, UT) connected to an irrigation controller (CS3500; Acclima). A TDT sensor was inserted into the substrate at an approximate 45° angle in one of the five pots in a row,

and irrigation of all five pots was based on the θ reading of that sensor. The sensors were connected to the irrigation controller, which measured the sensor output every 10 min, providing readings of θ (but not calibrated for our substrate) and temperature. Bulk EC was measured twice a day. Each irrigation line also had a flow meter (DLJ50; Daniel L. Jerman Co., Hackensack, NJ) to monitor water use in each experimental unit. Each plant was watered using a pressure-compensated drip emitter (2 lph; Netafim USA, Fresno, CA) with a spaghetti tube going to each pot. To allow establishment of the plants, θ was maintained at $0.429 \text{ m}^3 \cdot \text{m}^{-3}$ for 1 week before the treatments started.

The irrigation controller was programmed to maintain six θ set points, each replicated twice. Set points programmed into the irrigation controller were 5%, 12%, 19%, 26%, 33%, and 40%. After applying our substrate-specific calibration to the TDT sensor readings, these set points corresponded to actual θ levels of 0.136, 0.210, 0.281, 0.348, 0.412, and $0.472 \text{ m}^3 \cdot \text{m}^{-3}$. When the θ dropped below the set point, the irrigation controller opened the corresponding solenoid valve for 15 s, thus applying $\approx 8.3 \text{ mL}$ of water to each plant. To configure the irrigation system, and to establish the irrigation protocols described, the Irrigation Manager software (Acclima) was used.

The experiment was conducted in a glass-covered greenhouse at the University of Georgia in Athens, GA (lat. 34° N, long. 84° W). Environmental conditions in the greenhouse were monitored using a temperature/relative humidity sensor (HMP50; Vaisala, Woburn, MA) and a photosynthetic photon flux (PPF) sensor (SQ-100; Apogee Instruments, Logan, UT) connected to a datalogger (CR200; Campbell Sci. Inc., Logan, UT). Sensors were measured every minute to obtain daily averages and minimum and maximum values. Daily light integral (DLI; $\text{mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$) was calculated by integrating the PPF measurements throughout the day. Daily minimum and maximum temperatures were 18.0 ± 2.3 °C and 26.9 ± 3.2 °C, daily minimum and maximum relative humidity $46\% \pm 18\%$ and $82\% \pm 7\%$, and the DLI was $13.7 \pm 6.8 \text{ mol} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ (mean $\pm$ sd) over the 66 d of the experiment.

Because there was no leaching, except for the first 5 d at the $0.472 \text{ m}^3 \cdot \text{m}^{-3}$ threshold, total evapotranspiration of each group of plants was determined as the sum of the total amount of water applied as determined from flow meter readings plus the change in the amount of water in the substrate during the experiment as determined from the initial and final θ measurements and the volume of the pots $[(\theta_{\text{initial}} - \theta_{\text{final}}) \times 3.65 \text{ L}]$.

Independent measurements of soil volumetric water content and electrical conductivity. To obtain independent data for evaluation of the accuracy of the TDT sensors, weekly measurements of θ , and bulk and pore water EC were taken with a Theta probe (Delta-T devices, Cambridge, U.K.) and Sigma probe (Delta-T devices), respectively. The

Sigma probe measures bulk EC and calculates the pore water EC as described by Hilhorst (2000). Bulk EC is a measure of how well the substrate (including air, solution, and substrate particles) conducts electricity, whereas pore water EC determines the EC of the solution in the substrate. For Theta probe measurements, a calibration developed specifically for soilless substrates (Nemali et al., 2007) was used. A total of four pots per experimental unit was measured each time.

Measurements at the end of the experiment. Stomatal conductance and P_n were measured at midday using a leaf photosynthesis system (CIRAS-1; PP Systems, Amesbury, MA) and instantaneous water use efficiency was calculated as P_n/g_s . The air flow rate through the cuvette was $200 \text{ mL} \cdot \text{min}^{-1}$ with a CO_2 of $420 \text{ } \mu\text{mol} \cdot \text{mol}^{-1}$, an air temperature of 20 °C, a vapor pressure deficit of 1.6 kPa, and a PPF of $2000 \text{ } \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. The measurements were made on four plants per replication. Chlorophyll fluorescence was also measured on four leaves per replication using a pulse-modulated fluorometer (mini-PAM; Walz, Effeltrich, Germany). The method and parameters determined were the same as described by Sheng et al. (2008) but with an actinic light of $510 \text{ } \mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ for the light-adapted measurements.

At final harvest, the area of one fully expanded leaf from the upper one third of the canopy of each plant was determined using a leaf area meter (LI-3100; LI-COR Biosciences, Lincoln, NE). Shoot dry weight (DW) was determined after drying the shoots in a convection oven at 60 °C.

Experimental design and statistical analysis. The design was a randomized complete block with six treatments and two replications. Experimental units consisted of groups of five plants, one of which had a TDT sensor in the pot to control irrigation. Data collected at the end of the experiment were subjected to analysis of variance (ANOVA) (StatGraphics Plus 5.1; StatPoint Technologies, Warrenton, VA). When the ANOVA indicated significant effects ($P < 0.05$), means were separated using Fisher's least significant difference. Regression analyses were performed using SigmaPlot 10.0 (Systat Software Inc., San Jose, CA).

Results and Discussion

Calibration of sensors. There was an almost perfect, quadratic relationship between the θ as measured by the TDT sensors and the weight-based measurement of θ of the substrate (Fig. 1). Because the different θ calibration points were obtained with 12 different TDT sensors, these calibration results also indicate that there are no major differences among different sensors. However, the standard calibration for the TDT sensors was not accurate for the soilless substrate used in our study. The TDT sensors consistently underestimated θ , which resulted in errors of up to $0.08 \text{ m}^3 \cdot \text{m}^{-3}$. Estimation of θ using dielectric sensors is based on the ability of sensors to measure the "real" part of the dielectric permittivity (ϵ) or a property directly related

to ϵ . The total ϵ of a soil depends on the ϵ of the air ($\epsilon \approx 1$), soil solids (≈ 2 to 9), and water (≈ 80) in the soil (Blonquist et al., 2006). Because water has a much higher ϵ than air or soil solids, the overall ϵ of a soil is closely related to θ . However, ϵ differs among different soils and substrates, thus affecting the calibration of the sensors. By performing a substrate-specific calibration, we were able to convert the TDT measurements to the actual θ of the soilless substrate. The TDT sensors were not able to measure the θ of very dry substrate (less than $0.08 \text{ m}^3 \cdot \text{m}^{-3}$) because the sensors consistently read $0 \text{ m}^3 \cdot \text{m}^{-3}$ in such dry substrates (results not shown). Blonquist et al. (2005a) concluded that TDT sensors had the accuracy of time domain reflectometry sensors in determining θ under laboratory conditions and were less affected by bulk EC and temperature than other, lower frequency (50 MHz) sensors (Blonquist et al., 2005b).

Substrate water content control. The θ readings of the TDT sensors were close to the threshold θ (average θ levels, based on our calibration, were 0.146 , 0.212 , 0.285 , 0.350 , 0.415 , and $0.474 \text{ m}^3 \cdot \text{m}^{-3}$, 0.002 to $0.010 \text{ m}^3 \cdot \text{m}^{-3}$ above the threshold) and with little variation once the threshold θ was reached (Fig. 2). The sd between daily θ means was higher in the driest treatment ($0.0044 \text{ m}^3 \cdot \text{m}^{-3}$ versus $0.0020 \text{ m}^3 \cdot \text{m}^{-3}$ in the wettest treatment), which is consistent with previous findings (Nemali and van Iersel, 2006; van Iersel et al., 2010). This may be the result of the decreased hydraulic conductivity of peat-based substrates at lower water contents (Naasz et al., 2005), which slows water movement through the substrate and may result in a less uniform water distribution (van Iersel et al., 2010).

Fluctuations in θ were ≈ 13 times smaller than those reported by Nemali and van Iersel (2006). One of the reasons for the very stable θ could be the short irrigation time (15 s) used applying only 8 to 9 mL per irrigation event, much smaller than the 100 mL applied by Nemali and van Iersel (2006). van Iersel et al. (2010) reported that reducing the amount of water applied per irrigation event reduced fluctuations in θ .

The θ in the $0.472 \text{ m}^3 \cdot \text{m}^{-3}$ treatment increased on Day 5 because the substrate had to be slightly compacted to avoid continuous leaching and improve contact between the substrate and sensor. On Day 55, there was a small θ decrease in all treatments because of problems with the water supply. This decrease was less evident in the driest treatment, probably as a result of its lower evapotranspiration.

Theta and Sigma probe correlations. There was a strong, quadratic relationship between the TDT sensor readings (using our substrate-specific calibration) and the Theta probe measurements of θ over the course of the experiment ($R^2 = 0.91$) (Fig. 3). Theta probe readings were always lower than those of the TDT sensors, likely because the Theta probe only measures approximately the top 6 cm of the substrate, whereas the TDT sensors explore nearly the entire depth of the pot and the top part of a substrate normally is drier

Fig. 1. The relationship between the substrate water content (θ) of a bark-based soilless substrate, as measured by time domain transmissometry (TDT) sensors using the factory calibration for mineral soil, and the θ determined based on wet and dry weight and volume of the substrate (volumetric θ). At a volumetric θ below $0.08 \text{ m}^3 \cdot \text{m}^{-3}$, the TDT sensors read $0 \text{ m}^3 \cdot \text{m}^{-3}$ and those data were not included in the calibration.

Fig. 2. Average substrate volumetric water content (θ) readings of the time domain transmissometry sensors over a 66-d period, during which begonias were grown in 3.65-L pots. A substrate-specific calibration (see Fig. 1) was used to determine θ . Dashed lines indicate the θ threshold at which the containers in the various treatments were irrigated. Error bars indicate the sd ($n = 2$).

than the bottom part (Wallach, 2008). Overall, the TDT sensor can be considered a good θ sensor for soilless substrates, because it can be calibrated for such substrates and is responsive to changes in θ . Furthermore, its readings are strongly correlated with those of the Theta probe, which has been reported to be accurate in soilless substrates with little sensitivity to temperature or EC (Nemali et al., 2007).

The bulk EC measured with the TDT sensor had a weak correlation with pore water EC ($r^2 = 0.30$) and a moderate correlation with the bulk EC ($r^2 = 0.53$) as measured with the SigmaProbe (Fig. 4). One of the factors causing these poor correlations was that the bulk EC measured by the TDT sensors was almost always $0 \text{ dS} \cdot \text{m}^{-1}$ at θ below $0.28 \text{ m}^3 \cdot \text{m}^{-3}$. These results suggest a limited usefulness of the TDT sensors for bulk EC

measurements in soilless substrate. On the other hand, the use of a controlled-release fertilizer may increase variability in the data, because the SigmaProbe measures only a small volume of substrate. This may result in inconsistent readings if the EC of the substrate is not uniform as may be the case with controlled-release fertilizers. The poor correlation between TDT sensor bulk EC measurements and pore water EC is not surprising, because pore water EC depends on substrate properties, the dielectric permittivity (and thus θ), and the bulk EC (Hilhorst, 2000).

Evapotranspiration and plant growth. The evapotranspiration increased linearly as the threshold θ increased ($r^2 = 0.68$) (Fig. 5). Leaching was only noticed during the first 5 d of the experiment and only in the $0.472\text{-m}^3\cdot\text{m}^{-3}$ treatment. Average evapotranspiration over the 66-d experiment was $64\text{ mL}\cdot\text{d}^{-1}$ in the $0.472\text{-m}^3\cdot\text{m}^{-3}$ treatment and only $22\text{ mL}\cdot\text{d}^{-1}$ in the $0.136\text{-m}^3\cdot\text{m}^{-3}$ treatment. Conover (2010) reported an average water use of angel-wing begonias (*Begonia coccinea*) of $68\text{ mL}\cdot\text{d}^{-1}$, similar to that at our highest θ threshold. van Iersel et al. (2010) also reported increasing water use with increasing threshold θ but with a much stronger correlation ($r^2 = 0.89$). On the other hand, Burnett and van Iersel (2008) saw leaching and excess irrigation at the highest θ threshold, resulting in a quadratic relationship between θ and water use. The leaching at the beginning of our experiment may explain the high sd in the $0.472\text{-m}^3\cdot\text{m}^{-3}$ treatment, but there is no apparent reason for the high variability in the $0.348\text{-m}^3\cdot\text{m}^{-3}$ treatment (Fig. 5). This may have been caused by differences in plant size or micro-climatic conditions.

Shoot DW increased as the θ threshold increased, but there were no statistical differences in DW at a θ of $0.348\text{ m}^3\cdot\text{m}^{-3}$ or above (Table 1). Burnett and van Iersel (2008) found a linear growth response in gaura and van Iersel et al. (2010) a quadratic response in petunia with little additional growth above a threshold of $0.25\text{ m}^3\cdot\text{m}^{-3}$.

There was a quadratic relationship between evapotranspiration and shoot DW. Shoot DW increased linearly as evapotranspiration increased from 1.3 to 3.1 L (Fig. 6). The slope of the regression line is an estimate of the water use efficiency of the plants, indicating that the plants could produce 3 g of dry matter for every liter of water used. This is similar to the $2.54\text{ g}\cdot\text{L}^{-1}$ reported for petunia under greenhouse conditions with θ ranging from 0.05 to $0.40\text{ m}^3\cdot\text{m}^{-3}$ (van Iersel et al., 2010). When evapotranspiration exceeded 3.1 L/plant, there was a tendency for a decrease in DW with increasing evapotranspiration. This could be the result of over-irrigation negatively impacting root activity. Nemali and van Iersel (2006) reported a similar behavior in four bedding plants species, in which the highest threshold θ tended to reduce shoot DW.

The area of the fully expanded leaf was greatly reduced by low θ (Table 1). Such leaf area reduction is a well-known drought

Fig. 3. The relationship between substrate volumetric water content (θ) measurements by time domain transmissometry (TDT) sensors (using our substrate-specific calibration) and a Theta probe. Data were collected weekly in pots that were irrigated when θ dropped below one of six different θ thresholds.

Fig. 4. The relationship between bulk electrical conductivity (EC) measurements collected with time domain transmissometry (TDT) sensors and the pore water EC (top) and bulk EC (bottom) as measured using a SigmaProbe.

Fig. 5. Cumulative evapotranspiration from treatment initiation until the termination of the experiment (66 d) as a function of the substrate volumetric water content (θ) threshold at which begonias were irrigated.

Table 1. Effect of different volumetric water content (θ) threshold values for irrigation scheduling on stomatal conductance (g_s), net photosynthesis (P_n), instantaneous water use efficiency (WUE_i), area of the fully expanded leaves, and shoot dry weight (DW) of *Begonia semperflorens* after 2 months of irrigation using an Acclima CS3500 irrigation controller.

$\theta_{\text{threshold}}$ ($\text{m}^3 \cdot \text{m}^{-3}$)	g_s ($\text{mmol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)	P_n ($\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)	WUE_i ($\mu\text{mol} \cdot \text{mol}^{-1}$)	Leaf size (cm^2)	Shoot DW (g)
0.136	73 b*	9.1 c	128 a	37.0 c	2.20 d
0.210	166 a	14.7 a	109 ab	61.0 ab	4.06 c
0.281	168 a	12.4 ab	76 b	55.9 b	4.34 bc
0.348	189 a	14.3 a	80 b	68.3 ab	5.98 ab
0.412	135 a	10.9 bc	82 b	74.8 a	5.99 ab
0.472	174 a	12.2 ab	73 b	68.9 ab	6.50 a

*Means within a column followed by the same letter are not significantly different ($P < 0.05$).

Fig. 6. Shoot dry weight of begonias as a function of total evapotranspiration since the start of the irrigation treatments. The quadratic regression curve was fitted to all data points, whereas the linear regression includes only those treatments that did not receive excess water (open symbols). The slope of this regression line is an estimate of the water use efficiency of the begonias.

response, reducing the transpiring surface area of many species, e.g., oleander (*Nerium oleander*) (Bañón et al., 2005) and gaura (Burnett and van Iersel, 2008). The area of the fully expanded leaf was strongly and positively correlated with shoot DW ($r^2 = 0.93$) (data

not shown), suggesting that reduced leaf elongation may be partially responsible for growth reductions under drought conditions.

Photosynthetic activity. The P_n and g_s were reduced and the instantaneous water use efficiency increased at the $0.136 \cdot \text{m}^3 \cdot \text{m}^{-3}$ thresh-

old, but they were similar among the other treatments (Table 1). Earl (2003) also found that P_n and g_s in soybean and cotton were only decreased in the most severe drought treatment (a substrate water content of 20% of container capacity). There were no treatment differences in maximum quantum yield of photosystem II ($F_v/F_m = 0.80$), photosystem II efficiency ($\phi_{PSII} = 0.16$), and non-photochemical quenching ($NPQ = 2.28$). Similar ϕ_{PSII} in all treatments and lower P_n in the lowest θ treatment suggest that this treatment may have had increased photorespiration, a normal response to drought (Maxwell and Johnson, 2000; Wingler et al., 1999). Cha-um and Kirdmanee (2010) found that F_v/F_m and ϕ_{PSII} of eucalyptus (*Eucalyptus camaldulensis*) were not sensitive to drought stress, although P_n and NPQ decreased under severe drought. The F_v/F_m results indicate that photosystem II is not damaged by this level of drought (Maxwell and Johnson, 2000), which is consistent with the suggestion of Fracheboud and Leipner (2003) that chlorophyll fluorescence is not a very useful indicator for drought stress in C3 plants. However, the drought stress resulted in morphological and physiological changes (stomatal closure, reduction of leaf size) in the begonias to reduce water loss, but also reduced growth. The strong correlation between leaf size and shoot DW is consistent with findings by Montesano and van Iersel (2007), who found that growth reductions of tomato (*Solanum lycopersicum* L.) exposed to salinity stress are caused more by effects on leaf elongation than by effects on leaf photosynthesis.

Conclusions

The TDT sensors provide accurate measurements of θ after a substrate-specific calibration. The CS3500 irrigation controller, using TDT sensors, accurately maintained θ readings at different, user-specified levels. Growth of begonias was reduced by a θ threshold below $0.348 \cdot \text{m}^3 \cdot \text{m}^{-3}$. The lowest threshold θ ($0.136 \cdot \text{m}^3 \cdot \text{m}^{-3}$) reduced shoot DW, leaf area, leaf photosynthesis, and g_s . However, photosystem II was not damaged by the drought stress. Overall, shoot DW was much better correlated with the area of the uppermost fully expanded leaf than with leaf photosynthesis. This suggests that drought effects on plant growth are caused more by reductions in photosynthetically active surface area than by photosynthesis per unit leaf area.

The CS3500 irrigation controller, using TDT sensors, was able to irrigate plants as needed, suggesting that it can be used for irrigation control of container-grown crops as well as for drought stress research. The CS3500 irrigation controller has the advantage that it is commercially available and easy to install without the need for programming knowledge. As a result of the length of the TDT sensors, their use will be limited to pots of at least 20 cm height. Although the TDT sensors also measure bulk substrate EC, further research must be done to test its value. Under our experimental conditions (soilless substrate and slow-release fertilizer), the TDT sensor generally measured

a bulk EC of $0 \text{ dS}\cdot\text{m}^{-1}$ at θ below $0.28 \text{ m}^3\cdot\text{m}^{-3}$, which would limit its usefulness.

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