Tensiometric Monitoring of Container Substrate Moisture Status

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SUMMARY. The objective of these experiments was to evaluate the use of tensiometers to monitor substrate moisture tensions for Metro-Mix 500 and 2 pine bark : 1 Canadian peat : 1 sand (PBPS, by volume) used for container-grown azalea *Rhododendron indicum* L. 'Mrs. G.G. Gerbing' and chrysanthemum (*Dendranthema grandiflora* Tzvelez.) 'Coral Charm.' Commercially available ceramic cups of two sizes, small [0.374 inch (0.95 cm) diameter and 1.125 inches (2.86 cm) long] and large [0.874 inch (2.22 cm) diameter and 3.0 inches (7.62 cm) long] were used to construct pressure transducer-equipped tensiometers. Data from these greenhouse experiments, indicate that either the small or large ceramic cup could be used to monitor substrate tensions at which water would be available to container-grown plants.

Previous research with container-grown plants indicated that multiple applications of water each day resulted in more growth than a single application (Beeson,

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1992). The substrate that received multiple applications would contain more water before an irrigation event than substrate that received a single irrigation and this could result in more of the applied water being absorbed by the substrate (Karam and Niemiera, 1994). To maximize the usefulness of this concept, real-time substrate moisture measurements are needed to schedule irrigation. This could be accomplished with a substrate moisture sensor and irrigation control based on preset substrate moisture tensions. Richards and Marsh (1961) used tensiometers to schedule irrigation and to indicate the amount of water to apply with each application. Pogue and Pooley (1988) recommended the use of tensiometers for managing any low volume irrigation system and as an essential tool to maximize water usage, crop vigor, yields, and plant quality.

Tensiometers measure soil matric potential, which can be related to soil moisture content. They are relatively inexpensive, but have a limited operating range [0 to 0.8 bar (80 kPa) of suction], a response lag time, require continuous maintenance, measure tension and not soil moisture, and require good contact with the soil or substrate.

Pressure transducers can be easily attached to tensiometers for digital conversion and data acquisition. Factors, such as, temperature and substrate physical conditions, entrapped air, and permeability of the ceramic can affect the response time of a tensiometer-pressure transducer system (Stone et al., 1986; Watson, 1967; Watson and Jackson, 1967). Tensiometer-mounted pressure transducer devices can be interfaced with microcomputer-based data acquisition and control systems for real-time monitoring of soil water potential (Meron et al., 1995; Stone et al., 1985; Testezlaf et al., 1996; Vellidis et al., 1990; Zazueta et al., 1985). Phene et al. (1988) recommended the use of real-time irrigation control for production systems characterized as high frequency scheduling, which is typical for greenhouse production. In this case, a real-time control system has the potential to result in water conservation.

Real-time measurements have not been used extensively in the ornamental horticulture industry because of the lack of technical information and adequate sensors. In container plant production, tensiometers are very sensitive to disturbances that result in loss of contact with

Fig. 1. Layout of the manifold setup used to monitor substrate moisture tensions of azalea (*Rhododendron indicum*) 'Mrs. G.G. Gerbing' and chrysanthemum (*Dendranthema grandiflora*) 'Coral Charm.' The pressure transducer was interfaced with computer software to enabled real-time evaluation of substrate moisture tension.

the substrate (Valiente, 1993). Despite this limitation, tensiometers have been used in potted plant production to automatically schedule irrigation at different moisture tensions (Burger and Paul, 1987; Lieth and Burger, 1989; Testezlaf et al., 1996). Zazueta et al. (1994) developed a modified tensiometer in which the substrate rested on a porous plate. The objective of our study was to evaluate two different sizes of ceramic cups positioned horizontally to monitor the moisture tension of two substrates.

Materials and methods

EQUIPMENT. Two sizes of ceramic cups [0.374 inch (0.95 cm) diameter and 1.125 inches (2.86 cm) long and 0.874 inch (2.22 cm) diameter and 3.0 inches (7.62 cm) long] were used to construct pressure transducer-equipped tensiometers. The large cups were taken from standard 1-bar (100-kPa) tensiometers (model 2710-ARL; Forestry Supplies Inc., Jackson, Miss.). The small cups were also 1 bar (Q-Com, Inc., Irvine, Calif.). Manifold systems with four outlets each were built to connect four tensiometer probes to one pressure transducer. In Fig. 1, is a layout of the manifold setup. A medical three-way stopcock (Baxter Healthcare Corp., Valencia, Calif.) was installed in each manifold. This device was used for a syringe access to purge the system.

The piezoresistive-type pressure transducers (MPX5100 DP; Motorola Semiconductor Products Inc., Phoenix, Ariz.) were chosen based on their low cost, high level analog output, operating pressure range, and accuracy

[$\pm 2.5\%$ over 0 to 185 °F (85 °C)]. The pressure range of these transducers is from 0 to -1 bar (-100 kPa) and produces an analog electrical output from 0 to 5 v for 5 v direct current (VDC) supplied voltage. The voltage-pressure regression of the transducer's response was linear ($R^2 = 0.99$) and significant at 1% (Testezlaf et al., 1997). To ensure adequate power to the transducers, a separate regulated power supply was used during the experiments.

A data acquisition and control system (model 570; Keithley Metrabyte, Cleveland, Ohio) with 12 bits resolution with 16 differential input channels, was used for data acquisition. A graphical user interface developed and evaluated by Testezlaf et al. (1995) was used to continuously monitor the soil moisture tension.

EXPERIMENTAL DESIGN. Two experiments were established separately for two container-grown species, azalea (*R. indicum*) 'Mrs. G.G. Gerbing' and chrysanthemum (*D. grandiflora*) 'Coral Charm.' Both experiments consisted of factorial combinations of tensiometer ceramic cup sizes (small and large) and container substrate type (commercial and grower blended substrate). Four plants were randomly assigned to each of four pressure transducer assemblies, and these units were arranged in a completely randomized design. Experiments were conducted under greenhouse conditions at the University of Florida, Gainesville.

EXPERIMENT 1. On 12 Feb. 1996, multiple branched liners of azalea ('Mrs. G.G. Gerbing') plants were potted in 3.4-qt (≈ 3 -L) nursery containers [6.25 inches (15.8 cm) diameter by 6.50 inches (16.5 cm)] using either Metro-Mix 500

(Scotts-Sierra Horticultural Products Co., Marysville, Ohio) or 2 blended pine bark : 1 Canadian peat : 1 sand mix (PBPS, by volume). Valiente (1993) determined the physical properties of both container substrates. The plants were watered and placed in a glass greenhouse ($\approx 450 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$) set for 54 °F (13 °C) night temperature and 84 °F (29 °C) day temperature. Daily irrigation was supplied as needed and a solution that contained (in ppm) 150 N, 10 P, and 30 K from NH_4NO_3 , KH_2PO_4 , and K_2SO_4 was applied weekly. The bench was lit with intermittent incandescent light 2200 to 0200 HR to stimulate root and shoot growth. When roots were visible on 50% of the substrate surface, the experiment was initiated.

Eight plants of similar development and size that were potted in Metro-Mix 500 and eight that were potted in PBPS were selected. From each group of eight, four containers were prepared with tensiometers with small cups, and four with large cups by drilling a hole in the container plastic wall using a wood boring spade bit. The manifold system was carefully purged and tensiometers were inserted horizontally in the center of the substrate. Diameter of holes facilitated a snug fit around the tensiometers. Four randomly chosen containers were assigned to each manifold. All container substrates were saturated for 24 h and drained for 2 h before experiment initiation. Container weights and substrate tensions were monitored during one dry cycle, from 4 to 14 Mar. 1996. The end of a dry cycle was defined when most plants showed wilting.

EXPERIMENT 2. On 22 Feb. 1996, chrysanthemum ('Coral Charm') plugs were potted (four per pot) in standard

Table 1. Cumulative water loss (g) for azalea (*Rhododendron indicum*) 'Mrs. G.G. Gerbing' grown in 3.4-qt (3-L) containers with either a 2 pine bark : 1 Canadian peat : 1 sand substrate (PBPS, by volume) or Metro-Mix 500 (MM) with small or large ceramic cups² (n = 4 $\pm$ SD).

Day	Small/PBPS	Small/MM	Large/PBPS	Large/MM
0	0 $\pm$ 0	0 $\pm$ 0	0 $\pm$ 0	0 $\pm$ 0
1	24 $\pm$ 11	30 $\pm$ 14	57 $\pm$ 31	53 $\pm$ 27
2	85 $\pm$ 17	96 $\pm$ 16	111 $\pm$ 26	88 $\pm$ 34
3	140 $\pm$ 27	145 $\pm$ 21	149 $\pm$ 19	138 $\pm$ 20
4	232 $\pm$ 40	264 $\pm$ 48	251 $\pm$ 54	242 $\pm$ 12
5	347 $\pm$ 52	389 $\pm$ 34	375 $\pm$ 49	343 $\pm$ 36
6	419 $\pm$ 42	475 $\pm$ 41	442 $\pm$ 45	420 $\pm$ 46
7	486 $\pm$ 46	547 $\pm$ 55	507 $\pm$ 30	480 $\pm$ 50
8	572 $\pm$ 54	643 $\pm$ 54	592 $\pm$ 46	563 $\pm$ 60
9	650 $\pm$ 59	741 $\pm$ 49	683 $\pm$ 47	650 $\pm$ 73
10	717 $\pm$ 56	817 $\pm$ 45	748 $\pm$ 32	738 $\pm$ 75

²Small = diameter of 0.374 inch (0.95 cm) and length of 1.125 inches (2.86 cm). Large = diameter of 0.874 inch (2.22 cm) and length of 3.0 inches (7.62 cm); 10 g = 0.35 oz.

Table 2. Tension readings (kPa) for azalea (*Rhododendron indicum*) 'Mrs. G.G. Gerbing' grown in a 3.4-qt (3-L) containers with either a 2 pine bark : 1 Canadian peat : 1 sand substrate (PBPS, by volume) or Metro-Mix 500 (MM) with small or large ceramic cups^z (n = 4 ± SD).

Day	Small/PBPS	Small/MM	Large/PBPS	Large/MM
0	1.0 ± 0.6	0.9 ± 0.4	0.8 ± 0.6	0.9 ± 0.5
1	1.3 ± 0.7	1.1 ± 0.5	1.0 ± 0.3	1.1 ± 0.3
2	1.2 ± 0.4	1.1 ± 0.4	1.1 ± 0.3	1.3 ± 0.3
3	1.4 ± 0.4	1.4 ± 0.4	1.3 ± 0.4	1.3 ± 0.4
4	1.7 ± 0.4	1.9 ± 0.6	1.5 ± 0.4	1.5 ± 0.5
5	2.1 ± 0.4	2.5 ± 0.2	2.0 ± 0.4	2.2 ± 0.3
6	2.9 ± 0.7	3.8 ± 0.7	2.5 ± 0.2	2.4 ± 0.7
7	3.3 ± 0.4	4.6 ± 0.2	3.2 ± 0.5	3.5 ± 0.8
8	6.0 ± 2.1	7.3 ± 0.9	5.7 ± 1.0	5.1 ± 2.3
9	10.0 ± 4.8	8.6 ± 2.6	8.6 ± 1.7	6.2 ^y
10	7.7 ± 2.3	6.3 ± 2.4	9.3 ± 2.6	7.4 ^y

^zSmall = diameter of 0.374 inch (0.95 cm) and length of 1.125 inches (2.86 cm). Large = diameter of 0.874 inch (2.22 cm) and length of 3.0 inches (7.62 cm); 1 bar = 100 kPa.

^yn = 1.

Fig. 2. Relationship between substrate tension (kPa) and cumulative water loss for azalea (*Rhododendron indicum*) 'Mrs. G.G. Gerbing' with small [diameter of 0.374 inch (0.95 cm) and length of 1.125 inches (2.86 cm)] or large [diameter of 0.874 inch (2.22 cm) and length of 3.0 inches (7.62 cm)] ceramic cups in 2 pine bark : 1 Canadian peat : 1 sand (PBPS, by volume) or Metro-Mix 500 (MM). 1 bar = 100 kPa.

3.4-qt nursery containers using the same two substrates. The same experimental procedure defined for azalea was used for chrysanthemum. Container weights and substrate tensions were monitored for two dry cycles, from 15 to 22 Mar. 1996 and from 27 Mar. to 3 Apr. 1996.

DATA ACQUISITION AND ANALYSIS. Daily afternoon measurements of container weights were made using a digital balance (≈1.0 g). Corresponding tension readings were obtained by the data

acquisition system, at the same moment weight readings were made. Each time the manifold position was changed for a container tension reading, a waiting period of 3 to 6 min was necessary for signal stabilization.

The cumulative daily water loss was determined by subtracting the weight obtained each day from the initial weight. To evaluate the effects of ceramic cup size and substrate, an analysis of variance was performed for each day. A variable called percent of cumulative water loss (PCWL) was estimated to evaluate the relationship between daily water loss and substrate water tension. It describes how much of the total container capacity was left in the container every day during the dry cycle. It is calculated by $PCWL = [(W_{cwl} - W_i) / (W_{cwi})] \times 100$, where W_{cwl} = total cumulative water loss in grams and W_i = cumulative daily water loss in grams at day i .

This variable was related to corresponding tension values by using an exponential function.

Results and discussion

EXPERIMENT 1. There was not a significant interaction between substrate type and sensor cup size for cumulative water loss or tension readings for each day. Cumulative water loss each day was not different due to substrate, and tension readings each day were not different due to sensors, except for day 6 ($P = 0.015$). Data for each day are shown in

Table 3. Cumulative daily water loss for chrysanthemum (*Dendranthema grandiflora*) 'Coral Charm' grown in 3.4-qt (3-L) containers with either a 2 pine bark : 1 Canadian peat : 1 sand substrate (PBPS, by volume) or Metro-Mix 500 (MM) with small or large ceramic cups^z (n = 4 ± SD).

Day	Small/PBPS	Small/MM	Large/PBPS	Large/MM
Water loss (g) for first cycle				
0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
1	96 ± 29	81 ± 26	86 ± 4	116 ± 9
2	196 ± 25	221 ± 25	196 ± 9	257 ± 14
3	250 ± 20	291 ± 26	244 ± 23	335 ± 12
4	379 ± 35	445 ± 36	353 ± 26	496 ± 21
5	456 ± 38	580 ± 51	441 ± 17	641 ± 28
6	584 ± 46	720 ± 39	551 ± 29	795 ± 37
7	667 ± 33	879 ± 43	649 ± 39	939 ± 21
Water loss (g) for second cycle				
0	0 ± 0	0 ± 0	0 ± 0	0 ± 0
1	56 ± 15	86 ± 15	56 ± 21	82 ± 17
2	136 ± 24	192 ± 20	116 ± 23	199 ± 19
3	188 ± 22	281 ± 20	170 ± 20	283 ± 6
4	270 ± 31	384 ± 46	247 ± 22	405 ± 11
5	371 ± 44	592 ± 54	362 ± 31	607 ± 10
6	507 ± 39	849 ± 57	505 ± 33	857 ± 29
7	641 ± 50	1004 ± 58	641 ± 48	1017 ± 25

^zSmall = diameter of 0.374 inch (0.95 cm) and length of 1.125 inches (2.86 cm). Large = diameter of 0.874 inch (2.22 cm) and length of 3.0 inches (7.62 cm); 10 g = 0.35 oz.

Table 4. Substrate tension readings for chrysanthemum (*Dendranthema grandiflora*) 'Coral Charm' grown in 3.4-qt (3-L) containers with either a 2 pine bark : 1 Canadian peat : 1 sand substrate (PBPS, by volume) or Metro-Mix 500 (MM) with small or large ceramic cups^z (n = 4 ± SD).

Day	Small/PBPS	Small/MM	Large/PBPS	Large/MM
Tension readings (kPa) first cycle				
0	1.3 ± 0.3	0.9 ± 0.5	0.6 ± 0.4	1.0 ± 0.3
1	1.2 ± 0.5	1.4 ± 0.3	0.8 ± 0.5	1.4 ± 0.5
2	1.6 ± 0.5	1.6 ± 0.4	1.3 ± 0.4	2.1 ± 0.5
3	3.0 ± 0.9	2.4 ± 0.7	1.3 ± 0.5	2.6 ± 0.5
4	3.2 ± 0.8	5.3 ± 2.1	2.5 ± 0.6	5.9 ± 1.0
5	6.4 ± 2.0	8.6 ± 1.8	3.8 ± 1.2	13.3 ± 0.8
6	6.4 ± 1.3	10.2 ± 1.7	6.8 ± 1.7	---
7	10.2 ± 0.7	11.8 ± 3.7	10.7 ^y	---
Tension readings (kPa) second cycle				
0	0.7 ± 0.5	0.6 ± 0.2	0.6 ± 0.5	1.0 ± 0.7
1	1.3 ± 0.5	1.2 ± 0.6	1.0 ± 0.4	1.5 ± 0.4
2	2.5 ± 0.7	1.8 ± 0.9	1.2 ± 0.4	2.2 ± 0.5
3	2.4 ± 0.9	2.2 ± 0.7	1.5 ± 0.5	2.6 ± 0.6
4	2.0 ± 0.5	3.6 ± 1.0	1.6 ± 0.6	4.1 ± 0.7
5	3.6 ± 1.3	11.7 ± 3.7	2.5 ± 1.0	14.0 ± 0.4
6	6.3 ± 1.0	17.1 ± 6.1	5.5 ± 1.8	---
7	8.8 ± 2.6	33.7 ± 16.2	10.6 ± 2.8	---

^zSmall = diameter of 0.374 inch (0.95 cm) and length of 1.125 inches (2.86 cm). Large = diameter of 0.874 inch (2.22 cm) and length of 3.0 inches (7.62 cm).

^yn = 1, 1 bar = 100 kPa.

Fig. 3. Relationship between substrate tension (kPa) and cumulative water loss for chrysanthemum (*Dendranthema grandiflora*) 'Coral Charm' in the first and second cycle with small [diameter of 0.374 inch (0.95 cm) and length of 1.125 inches (2.86 cm)] or large [diameter of 0.874 inch (2.22 cm) and length of 3.0 inches (7.62 cm)] ceramic cups in 2 pine bark : 1 Canadian peat : 1 sand (PBPS, by volume) or Metro-Mix 500 (MM). 1 bar = 100 kPa.

Tables 1 and 2 and a scatter plot of the experimental data is shown in Fig. 2.

EXPERIMENT 2. Cumulative water loss and substrate tension readings for each day were tested for substrate × sensor interaction. For the first dry down cycle, interactions for water loss were not highly significant ($P \leq 0.01$) and the only highly significant interaction for tension occurred on day 5 ($P = 0.003$). There were no significant ($P \leq 0.05$) interactions for water loss or tensions during the second dry down cycle. Cumulative water loss due to substrate was

significant ($P \leq 0.05$) for days 2 to 7 of the first cycle and days 1 to 7 of the second cycle. This is contrary to Expt. 1, and is likely due to chrysanthemum roots exploiting the total container volume and not just the upper portion of the substrate as occurred with azalea. Consequently, more water was extracted from the Metro-Mix 500 because that substrate had a higher water holding capacity than PBPS. Tension readings were not different ($P \leq 0.05$) for sensors on days 0 to 7 of both cycles. However, it should be noted that tensions broke for the large sensors at day 6. Data for each day are shown in Tables 3 and 4 and a scatter plot is presented in Fig. 3.

WATER TENSION AND PCWL RELATIONSHIP. Data for chrysanthemum in Metro-Mix 500 was used to evaluate a relationship between tension readings and percent of cumulative water loss. Data generated with both sensors and both cycles were used for this analysis. Figure 4 shows the relationship between water tension and PCWL. The following exponential function below gave the best fit for this relationship: $\Psi_s = 27.18e^{-0.0336PCWL}$, $R^2 = 0.92$, where Ψ_s = substrate tension (kPa).

This equation can be used to define the value of the substrate water tension to start an irrigation event as a function of how much water will be available for the chrysanthemum plants. In Fig. 4, the function has a good fit for low values of tensions or high values of PCWL, which would occur shortly after a irrigation event. For example, at a PCWL of 60%, 40% of the water at container capacity had been lost and would correspond to a depletion of water available to the plant in most

Fig. 4. Relationship between tension (kPa) and percent of cumulative water loss (PCWL) for chrysanthemum (*Dendranthema grandiflora*) 'Coral Charm' grown in Metro-Mix 500. 1 bar = 100 kPa.

container substrates, indicating the need for irrigation.

Conclusions

Our data indicate that tensiometric ceramic cups 0.374 inch in diameter and 1.125 inches long or 0.874 inch in diameter and 3.0 inches long, may be used for monitoring the moisture tension of Metro-Mix 500 or 2 pine bark : 1 Canadian peat : 1 sand substrates. Tensiometers were inserted horizontally in the center of the substrate in 3.4-qt plastic containers. This required a minimal amount of time to cut a hole in the container sidewall and position a tensiometer. Tensiometers functioned reliably during the experiments, but for large ceramic cups, the tension may break near 0.1 bar (10 kPa). However, in most soilless substrates, water availability would be limited at this tension. Establishing the relationship between tension and available water would enable nursery operators to use real-time measurements to control irrigation for maximum water use efficiency.

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