Monitoring Effective Container Capacity: A Method for Reducing Over-Irrigation in Container Production Systems[1]

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Abstract

A gravimetric substrate moisture monitoring system was used to control irrigation frequency and volume within a narrow range of substrate moisture contents to study the effects of reduced irrigation volume on growth and water use of baldcypress (*Taxodium distichium* L.). The four irrigation treatments were: control (daily scheduled irrigation at 16:30 hours for 15 minutes or 6.75 liters (1.74 gal)/day) and 100, 80 and 60% of effective container capacity (ECC). Effective container capacity was defined as the maximum mass of a container, substrate and plant unit after gravitational water loss. Maintaining substrate moisture content at 80 and 60% ECC reduced baldcypress height, caliper, dry weight, and total plant N, P, and K content, but did not effect N, P or K concentrations compared to scheduled irrigation and 100% ECC treatments. Water use efficiencies (WUE, the volume of irrigation lost to evapo-transpiration divided by the total volume of irrigation applied) were determined for three dates. Plants under scheduled irrigation had WUEs of 17, 33, and 42% on July 8, July 24, and August 16, respectively. In contrast, WUE for plants under 100, 80 and 60% ECC treatments was 100% (no leachate) for the same dates. Plant water use under 80 and 60% ECC treatments was lower than that under scheduled and 100% ECC treatments. Plants under the 100% ECC treatment were 1.6 m (63 in) tall in August and used 2.6 liters (0.68 gal) of water per day. The gravimetric substrate monitoring system was an effective, plant-integrated method of reducing leachate volume that required minimal maintenance under the four month experimental period.

Index words: baldcypress, leachate, container capacity, effective container capacity, water use efficiency, evapo-transpiration rate, and substrate moisture content.

Significance to the Nursery Industry

To achieve high water use efficiency in container production requires both efficient irrigation delivery and monitoring. Gravimetric monitoring (weighing plants) was an effective method of controlling substrate moisture content and could be used to grow plants under zero irrigation leaching conditions. Baldcypress growth under the 100% effective container capacity treatment was similar to that under scheduled irrigation. The gravimetric system described can be operated under field conditions with minimal maintenance by anyone familiar with spreadsheets.

Introduction

Water is becoming one of the world's most precious resources. Legislation requiring nurseries to protect and preserve clean water has been enacted in several southern and western states. In Florida, legal restrictions in 2004 limited nursery irrigation amounts by 40% compared to 1992 levels, and tighter restrictions are likely due to the Clean Water Act (4). Thus, nursery producers must develop production methods that use less water without sacrificing plant growth or quality. Increasing the efficiency of irrigation delivery is one method of increasing water application efficiency. Water-application efficiency has been defined as the amount of water stored in the root zone compared to the total amount of water applied (12). In container production, 100% water-application efficiency equates with zero leachate.

A major increase in water-application efficiency occurred when growers shifted from overhead to micro-irrigation. For example, overhead irrigation application efficiencies ranged from 12–50% (8) while micro-irrigation application efficiencies ranged from 44 to 72% (14).

Cyclical or pulse irrigation (irrigating containers for several short periods with lower volume), compared to one or two irrigation events per day increased both water-application efficiency and plant quality (6, 13, 24). Increased plant quality was attributed to reduced daily accumulated plant water stress (6) and to reduced substrate temperatures (13). Increased water-application efficiency was attributed to increased lateral water movement (or alternatively, decreased channeling) in the substrate (14). An alternative approach is the Multi-Pot Box system that increases irrigation water use efficiency by capturing rainfall and excess irrigation in reservoirs with later delivery to the crop via sub-irrigation (11).

Water-application efficiency could be further increased if an efficient irrigation delivery system is coupled with a plant-integrated monitoring system. One monitoring approach uses relative ET-modeling and crop coefficients to estimate crop water needs (18). The ET-modeling approach has not been widely adopted because crop water coefficients are specific to each crop, production location, and period of the growing season (18). Modeling container crop water use has been demonstrated (3), but its practical application requires equipment not found in most nurseries and technical expertise beyond that of most nursery managers. Others have used plant water stress to control irrigation events; however significant lag times between stress onset and plant response have limited commercial adoption (9, 16, 21, 23).

Another approach monitors the substrate moisture content. Various instruments are available to monitor soil moisture (1, 17, 20), but none have been widely adopted for nursery production. Also, substrate moisture content is not evenly

[1]Received for publication March 20, 2007; in revised form August 8, 2007. Manuscript No. HCS-06-19. Salaries and research support provided by state and federal funds appropriated to the Ohio Agricultural Research and Development Center, The Ohio State University, the J. Frank Schmidt Family Charitable Trust, and the OARDC Industry Matching Grants program.

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distributed within a container (2); thus the appropriate location and orientation of substrate moisture sensor probes has not been determined.

For container-grown plants, the combination of container geometry and substrate physical properties dictates the maximum volume of plant-available water. The amount of water held by a substrate following saturation and gravitational water loss is termed container (field) capacity (10, 25). Container capacity can be determined gravimetrically. If substrate moisture content were monitored gravimetrically in real-time, then irrigation could be applied to plants within a narrow range of substrate moisture contents, resulting in 100% water application efficiency. Also, maintaining substrate moisture content at or near 100% container capacity will also increase plant growth (5, 7).

The objective of this study was to determine if gravimetric monitoring of a plant-substrate-container unit could be used to manage irrigation volume on a real-time basis and to study the effect of reduced irrigation volume on baldcypress (*Taxodium distichium* L.) growth, water use, and nutrient uptake.

Material and Methods

Preparation of plant material. In spring of 2004 recently germinated baldcypress seedlings were transplanted into 14 cm square, 15 cm deep (5.5 × 6.0 in) Spinout®-treated (Griffin Corp.,Valdasta, GA) plastic containers (250XL Nursery Supplies, Fairless Hills, PA) at the Howlett Hall greenhouses located on the Columbus campus of The Ohio State University. The substrate was Metro Mix 360 (Sun-Gro Horticultural Bellevue, WA). Seedlings were maintained weed free and watered twice daily with 100 ppm of 21N–2.9P–4.3K (21–7–7 Peters, Scotts Miracle-Gro Co., Marysville, OH) water-soluble fertilizer until September, when they were moved to a minimum heat polyhouse [4.4C (40F)] until the spring of 2005.

Forty baldcypress seedlings, selected for uniformity (height and caliper), were transplanted to #15 containers (Model No. 54.31l, [44.5 cm dia. × 40.6 cm deep (17.5 × 16 in) or 54.5 liter (14 gal)], Engineered Resins, Charlotte, NC) on June 1, 2005, and placed on a gravel production pad on the Columbus campus. The substrate was a pine bark, composted municipal sewage sludge (Com-til®, City of Columbus) 3:1 mix (by vol). At transplant, the seedlings were top dressed with 15N–7P–12K Osmocote (Scotts Miracle-Gro, Co., Marysville, OH) at 181.6 g (0.4 lb) of fertilizer per container. Plants were hand watered twice daily as needed until the study commenced on June 6, 2005. Stem caliper was taken 15 cm (6 in) above the substrate surface. Plant height was measured from the substrate surface to the shoot tip.

Total, air-filled and water-filled pore space were determined gravimetrically for the substrate using 54.4 liter (14 gal) containers. Five single container replications were used. Each container was lined with a plastic bag, placed on a balance and tared. The container was filled to within 2.5 cm (1 in) of the rim with water, the water height marked on the container and the weight recorded, which yielded the container volume. The container was emptied, filled with air-dried substrate to the volume mark, tared and then the substrate was saturated with water and allowed to equilibrate. The weight of water added represented an approximation of the total pore space of the substrate. Holes were then made in the plastic liner and the substrate allowed to for drain for one hour, after which the weight was recorded. The difference in the drained weight and the air-dried weight represents an approximation of the water filled pore space at field capacity. The difference in weight between the saturated and drained weights represents an approximation of the air-filled pore space at field capacity. The weights were converted to percent values by dividing by container volume and multiplying by 100.

Experimental procedures. Irrigation was delivered by one Spot Spitter (Roberts Irrigation, CA, model SS-AG 160 LGN) per container which, provided approximately 450 ml (0.12 gal) water/min. The seedlings were randomly assigned to one of four treatment groups each consisting of two replications with five plants per replication. Each replication had one indicator plant and four constituent plants. The irrigation treatments were: 1) one scheduled irrigation event at 16:30 hours daily for 15 min [a predicted irrigation volume of 6.75 liters/day (1.8 gal/day)]; 2) 100% of effective container capacity (ECC); 3) 80% of ECC; and 4) 60% of ECC. In this study, ECC represents the maximum mass of the container, substrate, and seedling after gravitational water has drained. Thus, ECC represents the weight of the container-substrate-plant unit plus the weight of the total substrate water holing capacity one hour after termination of an irrigation event.

On June 6, 2005, ECC for each of the indicator plants was determined by monitoring gravimetric changes at one-second intervals while all forty seedlings were irrigated. Gravimetric changes were obtained by placing each indicator plant on a balance connected to a computer. A macro written in Visual Basic for Applications (VBA) allowed the individual weights of the eight indicator plants to be collected and logged simultaneously into a spreadsheet. Irrigation was continued until the gravimetric changes held constant for twenty seconds, which we considered the effective saturation weight (ESW). Once ESW was reached, irrigation was discontinued and while the media drained gravimetric changes were monitored every second for the next hour or until a constant weight was obtained. The combined mass of the plant, container and substrate after one hour (or until a constant weight was obtained) was used as ECC and as the baseline or target weight for determining the initiation and termination of subsequent irrigation events.

A second macro written in VBA monitored all eight indicator plants throughout the study and logged their weights every 30 minutes. At each 30 minute interval, if the weight of an indicator plant was less than 9 g (0.02 lb) of its target weight, the solenoid controlling that indicator plant and the other four ‘crop’ plants within the replication was opened and remained open until the target ECC weight was recorded. When the target weight was reached, the solenoid was turned off. The accuracy of the balance was ± 9 g (0.02 lb), thus we chose a 9 g weight difference to trigger an irrigation event. Plant water use over a given time interval was determined by summing the irrigation volumes (as weights) for that period.

The ECC value may change during a production cycle due to plant growth, root growth into air-filled pore space, and decomposition of the organic fraction of the substrate. Therefore, ECC for each indicator plant was re-calculated on July 9 and August 8 during the season by using the procedure described above.

Monthly, stem calipers and plant heights were measured as described earlier. At the completion of the study all forty trees were harvested. All substrate was washed from the roots. Trees were then separated into roots and aerial parts (stems and leaves) and placed in a drying oven at 68C (155F) until a constant weight was obtained. Dry weights for each tree's parts were recorded. Dried root and aerial tissues of individual plant parts were ground to pass through a 2 mm (0.08 in) screen and 5 g (0.18 oz) sub-samples sent to the STAR Lab at the Ohio Agriculture and Research Development Center for macro-nutrition analysis (http://www.oardc.ohio-state.edu/starlab/). Total plant nitrogen (N), phosphorus (P), and potassium (K) content was determined by multiplying the N, P, K concentrations of each sub-sample by their respective dry weights and summing individual plant's root and aerial nutrient contents.

The data were analyzed using the one-way ANOVA procedure within SPSS (SPSS, Inc., Chicago, IL). Means were separated using the Student-Newman-Keuls test at $\alpha = 0.05$ level of significance.

Results and Discussion

Components of the irrigation monitoring system worked reliably under outdoor conditions. No maintenance was required during the four-month experimental period other than to re-boot the computer once following an electrical storm.

Substrate in the 54.4 liter (14 gal) containers averaged 46% total pore space. Air-filled and water-filled pore spaces were 18 and 28%, respectively. Initial ECC values averaged 26.65 kg (58.7 lb) on June 6 for the indicator plants. Effective container capacity weights were determined on two additional dates to correct for possible changes in ECC. There were no differences between treatment groups for ECC values measured on July 9 (26.29 kg or 57.8 lb) or August 8 (27.33 kg or 60.2 lb). Under the conditions of this experiment, there was little change in ECC during the experimental period.

On June 6 initial plant heights and calipers averaged 131 cm (52 in) and 14.2 mm (0.6 in), respectively (Tables 1 and 2). There were no differences in plant height or caliper until August 13 (Tables 1 and 2). From June 6 through July 22 the plants grew 9 cm (3.5 in) in height and 1.5 mm (0.06 in) in caliper (Tables 1 and 2). On August 13 and September 6 plant caliper in the 60% ECC treatment group was less than those in the 80% ECC, 100% ECC, and scheduled irrigation treatment groups (Table 2). Heights on August 13 and September 6 were similar for plants under the 60 and 80% ECC treatments and these were less than heights of those in the 100% ECC and scheduled irrigation treatments (Table 1).

Root, shoot and total plant dry weights of plants under the 100% ECC and scheduled irrigation treatments were greater than those under 60 and 80% ECC (Table 3). Shoot/root ratios were similar for all treatments (Table 3). Total plant dry mass accumulation for plants under the 100, 80 and 60% ECC treatment groups was 97, 81 and 67%, respectively, of plants under scheduled irrigation.

Growing plants under the irrigation control and monitoring system described was similar to growing plants under cyclic irrigation, but with more frequent irrigation cycles of lower volume. In other cyclic irrigation studies, plant growth or quality was greater than under a single daily irrigation event (5, 6, 7, 13, 22, 24). In contrast, there was no difference in baldcypress growth between once daily schedule irrigation and 100% ECC (cyclic) treatments. The lack of difference in

Table 1. Baldcypress height for four dates during a growing season. Plants were grown in trade 54.4 liter containers under different substrate moisture contents. Substrate moisture treatments were initiated in June.

	Height (cm)			
Treatment[z]	June 6	July 22	August 13	September 6
100% CC	127a[y]	137a	155a	167a
80% CC	128a	138a	144b	156b
60% CC	132a	139a	140b	154b
Scheduled	135a	145a	161a	170a

[z]Scheduled irrigation plants received 6.75 liters per day from one 15 minute irrigation event at 16:30 hours. Plants under the 100, 80 and 60% effective container capacity (ECC) treatments were irrigated if the indicator plant weight was 9 g less than treatment's target weight.

[y]Means within a column followed by different letters are different (α = 0.05) according to the Student-Newman-Keuls tests of significance. Each value is the mean of 10 plants.

Table 2. Baldcypress caliper for four dates during a growing season. Plants were grown in trade 54.4 liter containers under different substrate moisture contents. Substrate moisture treatments were initiated in June.

	Caliper (mm)			
Treatment[z]	June 6	July 22	August 13	September 6
100% CC	13.6a[y]	15.2a	19.4a	25.1a
80% CC	14.5a	15.8a	19.6a	22.2a
60% CC	14.8a	15.1a	16.6b	20.8b
Scheduled	14.2a	15.9a	19.9a	25.2a

[z]Scheduled irrigation plants received 6.75 liters per day from one 15 minute irrigation event at 16:30 hours. Plants under the 100, 80 and 60% effective container capacity (ECC) treatments were irrigated if the indicator plant weight was 9 g less than treatment's target weight.

[y]Means within a column followed by different letters are different (α = 0.05) according to the Student-Newman-Keuls tests of significance. Each value is the mean of 10 plants.

Table 3. September baldcypress dry mass after plants were grown under different substrate moisture contents in trade 54.4 liter containers for one growing season. Substrate moisture treatments were initiated in June.

	Dry mass (g)			
Treatment[z]	Roots	Shoots	Total plant	Shoot-to-root ratio
100% ECC	203.5a[y]	318.0a	521.3a	1.6a
80% ECC	171.7b	265.0b	436.7b	1.5a
60% ECC	149.5b	211.0b	360.5c	1.4a
Scheduled	202.9a	334.9a	537.8a	1.7a

[z]Scheduled irrigation plants received 6.75 liters per day from one 15 minute irrigation event at 16:30 hours. Plants under the 100, 80 and 60% effective container capacity (ECC) treatments were irrigated if the indicator plant weight was 9 g less than treatment's target weight.

[y]Means within a column followed by different letters are different (α = 0.05) according to the Student-Newman-Keuls tests of significance. Each value is the mean of 10 plants.

Table 4. **Baldcypress plant daily water use for three dates during a growing season. Plants were grown in trade 54.4 liter containers. Substrate moisture treatments were initiated in June.**

	Water use (ml per 24 hours)		
Treatment[z]	**July 8**	**July 24**	**August 17**
100% CC	1080.0a[y]	2250.0a	2632.5a
80% CC	1102.5a	1408.5b	1766.3b
60% CC	1061.1a	1170.0b	1732.5b
Scheduled	1102.5a	2153.3a	2767.5a

[z]Scheduled irrigation plants received 6.75 liters per day from one 15 minute irrigation event at 16:30 hours. Plants under the 100, 80 and 60% effective container capacity (ECC) treatments were irrigated if the indicator plant weight was 9 g less than treatment's target weight.

[y]Means within a column followed by different letters are different (α = 0.05) according to the Student-Newman-Keuls tests of significance. Each value is the mean of 10 plants.

plant size between once daily scheduled irrigation and 100% ECC treatments may be due to the relatively small-sized plants grown in large-sized containers used in this study compared with other studies. The 54.5 liter containers had 28% water-filled pore space and contained an estimated 15.2 liters (4.0 gal) of water. The maximum water use for the plants under scheduled irrigation was 2.8 liters (0.7 gal) on August 17 (Table 4). Thus, even with one irrigation event per day it is unlikely that the plants were water stressed.

Leachate electrical conductivity was not measured in this study because no leachate occurred in the 100, 80 and 60% ECC treatments. Under non-leaching irrigation treatments, substrate soluble salts would build up unless leached by rain events. In August and September, rainfall was 13 cm (5.0 in) and 9 cm (3.5 in) above average, respectively (Table 5). Thus, rainfall likely reduced the soluble salt levels in the 60, 80, and 100% ECC treatment groups and positively affected plant growth.

There were no differences in daily water use on the dates measured among plants in the four irrigation treatments on July 8; average daily water use was 1087 g (2.8 gal), Table 4). On July 24 and August 17, plants under the 100% ECC and scheduled irrigation treatments used more water per day than those under the 80 and 60% ECC treatments (Table 4). Plants under 100% ECC and scheduled irrigation had 65% higher water use than those under 60 and 80% ECC treatments on August 17. These dates were chosen because no rain occurred on the day of water use determination and for the two previous days and represent the only three-day rainless periods during the 2005 growing season.

Water use was equal to irrigation volume for plants under the 60, 80 and 100% ECC treatments (Table 4). Therefore, irrigation application efficiency in these treatment groups was 100% (no leaching attributed to irrigation events). Plants under scheduled irrigation received an average of 6.75 liters (1.72 gal) of water/day throughout the study. Plant water use under scheduled irrigation was similar to that of plants under the 100% ECC treatment. Because irrigation volume was delivered in excess of plant demand, water use efficiencies were 17, 33 and 42% on July 8, July 24, and August 17, respectively, for scheduled irrigation. Daily irrigation demand ranged from 1.1 liters (0.29 gal) in July to 2.7 liters (0.71 gal) in August.

Table 5. **Actual and average monthly rainfall amounts for June to September, Columbus, Ohio.**

	Rainfall (cm)	
Month	**Actual**	**Average**[z]
June	10.0	10.3
July	10.7	11.7
August	22.8	9.5
September	16.3	7.4

[z]30 year average for Columbus, OH obtained from http://lwf.ncdc.noaa.gov/oa/climate/online/ccd/nrmlprcp.html.

Plants in 100% ECC and scheduled treatments accumulated similar amounts of N, P, and K, but higher amounts than plants under the 60 and 80% ECC treatments (Table 6) because of greater dry mass; irrigation treatment had no effect on tissue nutrient concentrations (Table 6). Published foliar N concentration (1.79%, 15) were similar to the whole plant tissue N concentrations found in this study. However, foliar P (0.14%) and K (0.44 to 0.51%) levels were approximately half of those reported in Table 6.

Mineral nutrients are leached when irrigation volume exceeds container capacity (19). Thus, it is likely that fertilizer rates could be reduced under highly efficient irrigation application systems. Lower fertilizer rates would also reduce EC values in low leachate production systems.

The plant-integrated irrigation monitoring and control system described can be used to reduce leachate under diverse (with respect to taxa, substrate, container geometry, irrigation application devices, or diverse climatic conditions) container production systems. Under the system described, only the weight of the container-substrate-plant unit at ECC needs to be determined, as that weight represents the practical maximum water holding capacity for that unit. Monitoring weight changes to manage irrigation volume is easier, and less expensive, that using dielectric moisture sensors (17) or modeling (3). The method described here does not require sophisticated software, or technical expertise to operate. The system operated under outdoor conditions with minimal maintenance and within a similar range of substrate

Table 6. **Whole plant mineral nutrient content and nutrient concentration of baldcypress plants in September after growing under four substrate moisture levels.**

	Total plant (g)			Total plant concentration (%)		
Treatment[z]	**N**	**P**	**K**	**N**	**P**	**K**
100% CC	9.26a[y]	1.56a	6.11a	1.78a	0.29a	1.17a
80% CC	7.72b	1.12b	5.03b	1.77a	0.26a	1.15a
60% CC	6.23c	0.88b	4.00c	1.73a	0.24a	1.11a
Scheduled	9.25a	1.57a	6.67a	1.72a	0.29a	1.24a

[z]Scheduled irrigation plants received 6.75 liters per day from one 15 minute irrigation event at 16:30 hours. Plants under the 100, 80 and 60% effective container capacity (ECC) treatments were irrigated if the indicator plant weight was 9 g less than treatment's target weight.

[y]Means within a column followed by different letters are different (α = 0.05) according to the Student-Newman-Keuls tests of significance. Each value is the mean of 10 plants.

moisture content as described for a dielectric monitoring system (17).

Our study showed that substrate moisture content can be monitored gravimetrically to significantly reduce leaching and irrigation volume without compromising plant quality when baldcypress is irrigated at 100% ECC. Future research is needed to investigate the effects of reduced leaching fraction on plant growth in other production systems.

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