Testing an Automated Irrigation System Based on Leaching Fraction Testing and Weather in a Container Nursery

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Additional index words. CIRRIG, evapotranspiration, landscape plants, microcomputer, microirrigation, overhead, programmable logic controller, sprinkler

Summary. Irrigation scheduling in container nurseries is challenging due to the wide range of plant production conditions that must be accounted for at any given time. An irrigation scheduling system should also consider weather affecting evapotranspiration to apply proper amounts of water that will ensure optimal growth with minimal runoff (container drainage). We developed an automated system that relies on routine leaching fraction (leachate/water applied) testing and real-time weather recorded on-site to make adjustments to irrigation. A web-based program (CIRRIG) manages irrigation zone inputs [weather and leaching fraction (LF) test results] and outputs irrigation run times that can be implemented automatically with programmable logic controllers. In this study conducted at a nursery in central Florida, we compared the automated technology (CIRRIG) with the nursery's traditional irrigation practice (TIP) of manually adjusting irrigation based on substrate moisture status of core samples taken twice weekly. Compared with TIP, CIRRIG reduced water use in six of seven unreplicated trials with water savings being greater for microirrigated crops grown in large containers than for sprinkler-irrigated crops in small containers. Reduced pumping cost associated with water savings by CIRRIG was estimated to be $3250 per year, which was insignificant compared with the labor savings of $35,000 to $40,000 anticipated by the nursery using CIRRIG in lieu of TIP. At the end of the project, the necessary hardware was installed to expand CIRRIG nursery-wide and control 156 zones of irrigation.

Irrigation scheduling in a container nursery presents many challenges to water managers. One challenge is accounting for the variability in crop production conditions that exist at any given time in the nursery. It is common for container nurseries to have a wide variety of plants at several stages of production that require different amounts of irrigation water. Plants may be grown in different-sized containers ranging from small containers placed in high densities and irrigated with sprinklers to large containers (≥7 gal) placed in lower densities and irrigated with directed microirrigation, typically using spray stakes. A second challenge is accounting for the variability in the irrigation system's ability to deliver water uniformly within the irrigated area and at a rate that is consistent from day to day. System design and reliability play a large role in this regard. A third challenge is accounting for the variability in weather conditions that affect water loss through evapotranspiration (ET) as well as accounting for rain that may reduce the irrigation requirement. An irrigation scheduling strategy that considers these variables should provide an opportunity for conserving water while maintaining profitable plant growth and quality.

LF testing monitors the amount of leachate (container drainage) that results from irrigation. The LF is defined as the amount of leachate divided by the amount of irrigation water that was applied to the container. Because LF testing measures container drainage, which is considered the undesirable result of irrigation, it also provides a direct measurement of irrigation efficiency. If LF testing is conducted on representative plants in representative areas of each irrigation zone, and testing is routinely conducted to account for changing production conditions (e.g., growth flushes, pruning, spacing), then LF testing can help account for variability in water needs throughout the container nursery. Routine leaching fraction testing coupled with irrigation adjustment to maintain a target LF was found to reduce irrigation water use 43% in a Virginia nursery (Stanley, 2012). Decreased water use led to reduced costs associated with chlorine, electricity, fertilizer, and herbicide. Other benefits of reduced irrigation amounts included better crop uniformity and fewer disease problems. Despite these promising results, routine LF testing has not been widely adopted as an irrigation management practice.

Although LF testing can be used to make intermittent adjustments to irrigation, there is potential to further improve irrigation efficiency by making real-time adjustments to irrigation based on real-time weather collected on-site. We developed a web-based irrigation scheduling program called CIRRIG (Million and Yeager, 2015) that uses real-time weather to calculate potential rates of ET that provide an index for real-time adjustments to

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
102.7902	acre-inch(es)	m^3	0.0097
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
9.3540	gal/acre	$L\cdot ha^{-1}$	0.1069
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
1	ppm	$mg\cdot L^{-1}$	1
6.8948	psi	kPa	0.1450
10.7639	W/ft^2	$W\cdot m^{-2}$	0.0929
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

irrigation amounts. Compared with a Florida nursery's traditional irrigation practice of only making seasonal adjustments in irrigation run times, using CIRRIG to microirrigate a landscape plant in a trade 15-gal container decreased irrigation water use by 50% but also decreased plant growth 10% to 15% (Million and Yeager, 2019). Decreased plant growth was attributed in part to water stress that occurred despite using a target LF of 25% indicating that a target LF >25% may be required to maintain optimal growth with certain container substrates and/or irrigation systems. It should be noted that in this trial, irrigation was applied only once per day so that better irrigation water retention might have resulted if irrigation was scheduled for two or more cycles per day (Beeson and Haydu, 1994; Tyler et al., 1996). Although the results of this trial were promising, additional research was indicated to test the technology on a wider range of crops including sprinkler-irrigated plants and over greater production times.

The objective of this study was to further evaluate this CIRRIG strategy by implementing an automated CIRRIG irrigation system at a container nursery and comparing water use and plant growth of several landscape crops grown in small containers with sprinkler irrigation as well as in large containers with microirrigation. We include a brief economic evaluation of costs and benefits of the tested irrigation practice based on input from nursery staff.

Materials and methods

IRRIGATION TECHNOLOGY. The irrigation technology evaluated in this study involved a software component (CIRRIG) to automatically generate irrigation schedules and a hardware component, programmable logic controller (PLC), to automatically implement the schedules. A brief description of each component follows.

CIRRIG is an ET-based irrigation scheduling program designed for use in commercial container nurseries in the southeastern United States. Because weather is a major factor affecting ET, an important function of CIRRIG was to acquire and manage weather data obtained from a datalogging weather station (Vantage Pro Plus II; Davis Instruments, Hayward, CA) located on-site. A Linux-based microcomputer (Raspberry Pi 3 Model B; Adafruit Industries, New York, NY) running weeWX (Keffer and Wall, 2009), a free, open-source weather program, acquired weather data logged every 5 s from the weather station and parsed the weather data for four parameters used in ET calculations: minimum and maximum temperature, solar radiation, and rain. Weather data were stored in a MySQL database (Oracle, Redwood City, CA) under the nursery's user account on the CIRRIG server housed in Gainesville, FL. The past 48 h of weather were also stored on the microcomputer for local CIRRIG calculations.

CIRRIG allowed the nursery staff to create irrigation zones for each valve to be controlled automatically. Once a zone was created, additional information was input that remained unchanged or was infrequently changed during production of a given crop. These inputs included zone type (sprinkler or micro), number of irrigation cycles per day, irrigation rate, irrigation uniformity, minimum run time, and container diameter. A second section was used to input results of routine LF tests. LF test inputs included LF test time and date, LF irrigation run time (RT_{test}), measured LF (LF_{test}), and target LF (LF_{target}). Based on the LF test inputs, CIRRIG calculated two LF test reference values, ET_{LF} and RT_{LF}, for making future irrigation calculations. ET_{LF} was the reference potential ET value (ETo) calculated using the 24 h of weather data collected before the LF test date and time. ETo was calculated using a container-grown plant evaporation model described by Million et al. (2011), which used a biased temperature maximum that accounted for the heating affect that occurs when growing plants in black containers on black ground cloth in spaced arrangements. RT_{LF} was the run time of the LF test adjusted for the target LF according to the following equation.

$$RT_{LF} = (100\% - LF_{test}) \div (100\% - LF_{target}) \times RT_{test}.$$

Using the LF test reference values, daily irrigation run times (RT_d) were calculated just before irrigation according to: $RT_d = ETo/ET_{LF} \times RT_{LF}$ where ETo is the potential ET calculated using the past 24 h of weather data. To account for rain and multiple cycles during the day, an hourly water balance was calculated based on the distribution of solar radiation during the 24-h period:

$$RT_h = SR_h \div SR_d \times RT_d - RT_{rain},$$

where RT_h = hourly run time, SR_h = hourly solar radiation, SR_d = past 24-h solar radiation, and RT_{rain} = hourly rain converted to equivalent run time based on the irrigation application rate. RT_h values calculated for each hour after the last irrigation were summed and ultimately output as the current irrigation run time. If the designated minimum run time was not exceeded, then irrigation was cancelled, and the deficit carried over to the subsequent irrigation cycle. A daily history of CIRRIG outputs and supporting input data for each irrigation cycle were stored under the nursery's account for recordkeeping purposes.

A PLC system designed to interface with CIRRIG controlled solenoid valves in the field. The previously described microprocessor ran local JAVA (Oracle) agents that acquired output from CIRRIG and set timer values for corresponding outlets on the PLC (Direct Logic D0-DA06 with H0-ECOM100 communications module; Automation Direct, Atlanta, GA) via an Ethernet connection on the local network. We used a universal serial (USB) cellular modem with a static IP address and router (MBR95; Cradlepoint, Boise, ID) to create a local network connected to the internet. A University of Florida–designed graphical user interface allowed the control and monitoring of all PLC activities locally or remotely. A history of all PLC activities was also written to output text and html files.

TRIALS. All trials were conducted at Hibernia (HN), a wholesale container nursery located near the central Florida town of Webster (lat. 28.6°N, long. 82.1°W, elevation 92 ft). HN had several attributes that made them good cooperators for this study: 1) HN produced a wide array of landscape plants with both sprinkler and microirrigation, 2) they had a pressurized irrigation system with small (0.2 to 0.5 acre) areas controlled by one valve, 3) knowledgeable and interested staff

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and owner willing to assume management of the CIRRIG technology during the study.

Seven side-by-side, unreplicated trials comparing automated CIRRIG technology with the nursery's traditional irrigation practice were conducted for 2 years (Table 1). Paired, side-by-side trials were conducted as there were not enough irrigated zones containing the same crop for replicated trials. The plants tested included dwarf Burford holly (*Ilex cornuta* 'Burfordii Nana'), chinese fringe flower (*Loropetalum chinense* 'Plum'), Nellie Stevens holly (*Ilex* × 'Nellie R. Stevens'), Leyland cypress (*Cupressus* ×*leylandii*), and crape myrtle (*Lagerstroemia* × 'Natchez'). Three of the trials were sprinkler-irrigated crops in trade 3-gal containers, and four trials were microirrigated crops in trade 15-gal containers. Sprinkler zones were 60 × 400 ft and were irrigated with wobbler sprinklers (Xcel-Wobbler with gray #9 nozzles rated at 2.5 gal/min at 20 psi; Senninger, Clermont, FL) on 5-ft risers in three offset rows with a spacing of 25 ft between sprinklers in a row. Containers were grown on industry-standard, woven polypropylene ground cloth underlain by native sandy soil with little or no slope. The width of microirrigated production areas was 25 ft, which allowed nine rows of 17-inch-diameter containers to be placed in an offset pattern. Five 1-inch-diameter polyethylene pipes supplied water to the nine rows of plants via one spray stake assembly per container. Each spray stake assembly included a 3-ft section of 1/8-inch-diameter polyethylene tubing and one spray stake (Spot-Spitter; Primerus, Encinitas, CA). Trials M1, M3, and M4 used the Black High Flow spray stake with a 160° spray pattern and rated at 0.25 gal/min at 20 psi. Trial M2 used the Green Medium Flow spray stake with a 160° spray pattern and rated at 0.19 gal/min at 20 psi. Spray stakes were placed 1 to 2 inches inside the container wall pointing toward the center of the container.

Each of the trials had common procedures that were followed. Once a pair of irrigation zones was selected, flowmeters (M0304; McCrometer, Hemet, CA) were installed to monitor water use. Irrigation tests were conducted by UF staff in each test zone by collecting irrigation water in 20 collection pails placed throughout the irrigated area following an irrigation cycle of at least 30 min for sprinkler-irrigated zones and 4 min from microirrigated zones. Irrigation application rate and distribution of uniformity (DU; Haman and Yeager, 2015) were calculated and entered into CIRRIG for test zones to be irrigated by CIRRIG. The depth of water collected was used to relate depth of irrigation water applied per change in flowmeter reading (inches per 1000 gal for sprinkler-irrigated zones and gallons per plant per 1000 gal for microirrigated zones). During each trial, flowmeter readings were taken once or twice each week to monitor irrigation water applied to each crop.

Plant growth was monitored by labeling 20 similar-sized plants in each test zone. Plant height and width were measured at the start and then approximately every other week until the trial was ended. Plant height was measured from the top of the substrate to the uppermost foliage, and plant width was the average of two perpendicular width measurements. Trials were ended when the nursery began selling plants out of either one of the test zones.

The two irrigation practices compared for each trial were the HN's TIP and automated CIRRIG technology based on ET and LF testing (CIRRIG). For TIP, HN staff took core samples of container substrate in each zone two times per week and rated substrate moisture on a numeric scale. Staff met routinely as a group and, based on moisture ratings, agreed on any changes to the irrigation run times, which were then implemented by manually programming irrigation controllers (Sterling 8 Station; Buckner Superior, Torrance, CA). Irrigation was cancelled if staff deemed enough rain fell to satisfy irrigation demand. In general, sprinkler irrigation was scheduled once per day predawn, and microirrigation was scheduled two to three times per day typically starting at 0830, 1200, and 1500 HR.

For CIRRIG, irrigation was controlled automatically with PLC technology. CIRRIG irrigation start times were the same as TIP. For each trial, HN staff was responsible for conducting LF testing about once every 3 to 4 weeks and entering results into the CIRRIG program. LF testing was conducted on four plants per CIRRIG test zone. HN staff was directed not to conduct LF tests on days during periods of excessively cloudy weather when ET rates would be lower than normal. For LF tests in sprinkler areas, containers were placed in tight-fitting pails that allowed drainage water to collect without being

Table 1. Unreplicated trials conducted at a container nursery to compare automated CIRRIG technology with the nursery's traditional irrigation practice with regards to plant growth and water use. Average daily minimum (T_{min}) and maximum (T_{max}) temperatures and solar radiation and total rain were recorded on-site.

Trial[z]	Plant	Container size[y]	Start date	End date	T_{min}/T_{max} (°F)[x]	Solar radiation ($W \cdot m^{-2}$)[x]	Total rain (inches)[y]
S1	Dwarf burford holly	#3	1 Mar. 2016	15 June 2016	63/86	264	9.4
S2	Chinese fringe flower	#3	5 July 2016	21 Nov. 2016	67/87	191	11.5
S3	Dwarf burford holly	#3	10 Aug. 2017	15 Aug. 2018	61/83	191	60.2
M1	Nellie stevens holly	#15	1 Mar. 2016	20 July 2016	67/89	263	15.0
M2	Leyland cypress	#15	4 Oct. 2016	2 Mar. 2017	54/79	152	6.9
M3	Nellie stevens holly	#15	27 Mar. 2017	12 Feb. 2018	63/84	188	40.6
M4	Crape myrtle	#15	13 Apr. 2017	21 Aug. 2017	69/90	227	27.0

[z]S = sprinkler-irrigated, M = microirrigated.
[y]#3 = trade 3-gal [10-inch (S1, S2), 11-inch (S3)], #15 = trade 15-gal (17 inch); 1 inch = 2.54 cm.
[x](°F – 32) ÷ 1.8 = °C, $W \cdot m^{-2}$ = 0.0929 W/ft².

reabsorbed. Because staff left work before 1700 HR, LF container assemblies were weighed around 1600 HR to get a preirrigation weight. A preirrigation weight correction for the additional water loss occurring after 1600 HR was made by determining the additional weight loss of two plants removed from the irrigated area. After the one-time, predawn irrigation, each LF assembly was reweighed and the difference in pre- and postirrigation weights calculated as the amount of irrigation water applied. After removing the plant from the pail, the amount of leachate in the pail was determined by weighing and the LF calculated as the amount of leachate divided by the amount of irrigation water applied. The average LF of the four plants along with the irrigation run time and time and date of the test were entered into CIRRIG by HN staff. For microirrigated trials, LF plants were placed on 17-inch-diameter pizza pans raised above the ground on top of two 1-ft-long pieces of 4 × 4-inch lumber (Fig. 1). A single one-half-inch hole was punched near the perimeter of the pan to allow leachate to drain into a collection pan for weighing. If needed, slope was created with shims to improve drainage out of the pizza pan. To determine the amount of irrigation water applied to the container, an adjacent emitter was placed into a 4-gal pail. A one-half-inch-wide slot cut out of the rim allowed the tubing to pass into the pail with a lid on the pail. Leachate and irrigation water applied were collected and summed over all scheduled irrigation cycles in a 24-h period to arrive at one LF value per LF plant. As with sprinkler LF testing, the average of the four LF measurements was entered into CIRRIG by HN staff. LF setups with plants on the pizza pans were left in the CIRRIG test zone throughout each trial. All weights were recorded to the nearest 0.01 kg using a portable bench scale (ES30R; Ohaus, Parsippany, NJ).

Fig. 1. Leaching fraction testing was conducted routinely by nursery staff in both sprinkler (left) and microirrigated (right) test zones controlled by CIRRIG technology.

The container substrate was a 60% pine bark : 40% compost (S1, S2, M1, M2) or a 70% pine bark : 30% Florida sedge peat (S3, M3, M4). Each substrate was amended with dolomitic limestone, micronutrients, and a controlled-release fertilizer. The 70% pine bark : 30% sedge peat had a total porosity of 44% and a water-holding capacity 19%; the same data were not available for the 60% bark : 40% peat substrate. Additional fertilizer was applied to the substrate surface at HN's discretion. Three times per week during one irrigation cycle, microirrigation water was injected with soluble fertilizer to deliver 100 mg·L^{-1} nitrogen. Pruning was routinely practiced to control shape and growth of plants. Microirrigated plants were secured to a trellis system to prevent blow-over. Crape myrtle in 15-gal containers had five plants per container each attached to a bamboo stake. Crape myrtle plants were routinely pruned to encourage stem growth and limit shoot growth. Instead of measuring the size of the plant canopy, stem caliper of each of the five plants in the container was measured at a height of 6 inches above the substrate.

The trials were not replicated, so we could not conduct a statistical analysis of the effect of irrigation practice on plant growth and water use. For plant growth, we subtracted the initial plant size from the final plant size to calculate a change in plant height and change in plant width. A standard deviation was calculated to indicate the relative variability in the growth measurements of the 20 plants per test zone. For irrigation water use, we converted all measurements to an equivalent plant production basis (gallons per acre per day). To convert to inches per acre per day, we divided gallons per acre per day by 27,154.

Results and discussion

Hibernia staff quickly learned how to conduct LF tests and became familiar with some of the glitches that can occur during testing. For example, it was important to have an easy-to-use weighing method to eliminate taring mistakes that can give erroneous results. Another example was to plan ahead and conduct LF tests on days unaffected by cloudy or rainy weather. This can be frustrating in summer months when frequent afternoon rains can spoil a prepared test. A third example was to increase irrigation rates 10% to 20% before running the test to ensure that leachate will be collected. In general, this is especially true during the spring months when plants are rapidly growing and ET rates increasing with longer days and warmer temperatures.

SPRINKLER TRIALS. Results of sprinkler trials S1 and S2 indicated little effect of irrigation practice on irrigation water use (Table 2) and plant growth (Table 3). Plant growth with CIRRIG averaged 5% less than TIP with CIRRIG applying an average of 3% less irrigation water. LF tests indicated that CIRRIG was not excessively irrigating plants. LF tests averaged close to the target value of 15% with the highest LF values not exceeding 26% and 33% for S1 and S2, respectively (Table 4). Plants grown with CIRRIG were visually indistinguishable in size and quality from those grown with TIP.

Unlike S1 and S2, dwarf burford holly grown in S3 were irrigated through an entire production cycle starting with newly planted containers in a container-to-container (jammed) arrangement and ending in a spaced arrangement at the time of sale (Table 1). We observed throughout S3

Table 2. Effect of irrigation practice on irrigation water use at a wholesale container nursery. An automated irrigation schedule based on routine leaching fraction testing and weather (CIRRIG) was compared with the nursery's traditional irrigation practice (TIP) in side-by-side, unreplicated trials.

Trial[z]	Plant	Irrigation rate (per h)[y]	Test zone (acre)[x]	Plants (no.)	Plant density (no./acre)[x]	Time (d)	Water applied (gal/acre per day)[x] TIP	CIRRIG	C/T[w]
S1	Dwarf burford holly	0.31 inch	0.56	8640	15,430	106	5866	5636	0.96
S2	Chinese fringe flower	0.47 inch	0.56	8640	15,430	139	5900	5861	0.99
S3	Dwarf burford holly	0.47 inch	0.56	33,870[v]	45,630[u]	370	4850	6020	1.24
M1	Nellie stevens holly	13.4 gal	0.23	720	3130	141	4722	4149	0.88
M2	Leyland cypress	9.5 gal	0.23	784	3410	148	2984	2894	0.97
M3	Nellie stevens holly	14.4 gal	0.23[t]	622	2700	322	6716	4687	0.70
M4	Crape myrtle	13.2 gal	0.23	644	2800	130	7797	5406	0.69

[z]S = sprinkler-irrigated, trade 3-gal container; M = micro-irrigated, trade 15-gal container.
[y]1 inch = 2.54 cm, 1 gal = 3.7854 L.
[x]1 acre = 0.4047 ha, 1 plant/acre = 2.4711 plants/ha, 1 gal/acre = 9.3540 $L \cdot ha^{-1}$.
[w]CIRRIG/TIP.
[v]Spaced after 248 d (24 Apr. 2018) to 8840 plants/acre.
[u]Average plant density.
[t]CIRRIG test area was only 0.125 acre and contained 342 plants.

Table 3. Effect of irrigation practice on plant growth for seven side-by-side, unreplicated trials at a wholesale container nursery. An automated irrigation schedule based on routine leaching fraction testing and weather (CIRRIG) was compared with the nursery's traditional irrigation practice (TIP).

Trial[z]	Plant	Plant ht change (inches)[y] TIP Avg (SD)[w]	CIRRIG Avg (SD)[w]	C/T[x]	Plant width change (inches) TIP Avg (SD)[w]	CIRRIG Avg (SD)[w]	C/T
S1	Dwarf burford holly	3.5 (1.9)	3.2 (1.4)	0.91	6.9 (1.5)	6.7 (0.9)	0.97
S2	Chinese fringe flower	4.0 (2.5)	3.8 (1.7)	0.95	6.6 (1.1)	6.3 (1.6)	0.95
S3	Dwarf burford holly	7.0 (1.7)	8.6 (2.0)	1.23	6.5 (1.5)	8.0 (1.8)	1.23
M1	Nellie stevens holly	9.1 (4.6)	10.7 (5.7)	1.18	13.9 (3.8)	14.5 (3.3)	1.04
M2	Leyland cypress	16.5 (3.8)	16.5 (3.1)	1.00	11.1 (3.1)	10.8 (2.9)	0.97
M3	Nellie stevens holly	26.7 (5.5)	27.3 (5.3)	1.02	15.4 (2.5)	13.6 (1.8)	0.88
M4	Crape myrtle	—	—	—	10.3 (1.9)[v]	9.6 (1.8)[v]	0.93

[z]S = sprinkler-irrigated, trade 3-gal container; M = microirrigated, trade 15-gal container.
[y]1 inch = 2.54 cm.
[x]CIRRIG/TIP.
[w]n = 20.
[v]Change in stem caliper (millimeters) measured 6 inches above substrate (five stems/plant; n = 100); 1 mm = 0.0394 inch.

that CIRRIG was consistently applying more water than TIP. By the end of the trial CIRRIG applied a total of 24% more irrigation water than TIP (Table 2). LF tests indicated that CIRRIG was not overwatering as the average LF equaled the target LF of 15% and LF tests never exceeded 27% throughout the 370-d trial (Table 4). Plant growth was greater with CIRRIG than TIP indicating that TIP was likely underwatering the crop. The 24% increase in plant growth was visually apparent as plant canopies were denser and of better quality. HN staff observed that midseason root development was greater for CIRRIG plants, but no root data were taken.

Table 4. Target and measured leaching fraction (LF) values routinely measured in test zones irrigated with CIRRIG, an LF and weather-based irrigation scheduling program.

Trial[z]	Plant	LF (%)[y] Target	Mean	Min	Max
S1	Dwarf burford holly	15	13	8	26
S2	Chinese fringe flower	15	18	6	33
S3	Dwarf burford holly	15	15	6	27
M1	Nellie stevens holly	20	30	9	45
M2	Leyland cypress	25	32	19	46
M3	Nellie stevens holly	25	32	17	58
M4	Crape myrtle	25	38	11	65

[z]S = sprinkler-irrigated, trade 3-gal container; M = microirrigated, trade 15-gal container.
[y]Mean, minimum, and maximum values (average of four plants per LF test) for LF tests conducted routinely (once every 3–4 weeks) during each trial.

Microirrigation trials. CIRRIG reduced total irrigation water applied to the nellie stevens holly in M1 by 12% compared with TIP (Table 2). Most of the water savings with CIRRIG were obtained during the last 4 weeks of the 20-week trial when plants were growing slowly due to hot June and July weather and plants had reached a marketable size. The target LF for M1 was 20%, which we found to be difficult to maintain. The average LF during M1 was 30% even with routine CIRRIG adjustments to target a LF of 20% (Table 4). We believe the high-flow spray stake emitters may have contributed to the inability to maintain a low LF by exceeding the substrate's capacity to retain the irrigation water at the high application rate. For subsequent trials, we suggested adding a third irrigation cycle and changing the target LF from 20% to 25%. We also suggested using a lower flow spray stake emitter, but HN related to us that clogging problems have made them rely on the high flow rate emitters for most of their microirrigation production.

CIRRIG increased plant growth of nellie stevens holly compared with TIP but the differences in size and quality were not visually important. Change in plant height was increased 18% with CIRRIG, but the variability in plant height change was high as indicated by the high SD values (Table 3). Regardless of irrigation practice, plants were of marketable size and quality at the end of the trial.

For M2, CIRRIG and TIP had similar water use and plant growth results. The changes in plant height and width of leyland cypress irrigated with CIRRIG were within 3% of the changes in plant height and width of leyland cypress irrigated with TIP, and all plants were of excellent quality (Table 3). Total water applied was decreased by 3% using CIRRIG but this difference was not considered to be important. Compared with the other microirrigation trials, daily water use for M2 was lower, which was attributed to the trial occurring over the winter when ET rates were lower due to shorter days and cooler temperatures (Table 1). Although the target LF was increased from 20% to 25% and lower flow emitters were used, LF tests still exceeded the target, averaging 32%. Two LF tests were unusually high (89% and 90%), which we traced to a taring error. We omitted these two results from the average LF calculation. A benefit of finding the LF measurement error was to change HN's weighing method and to reinforce not using results that are questionable and, when in doubt, to repeat the LF test as soon as possible. This underscored for us the importance of staff training to ensure that accurate and reliable results are being input into CIRRIG.

CIRRIG reduced total water applied to nellie stevens holly in M3 by 30% (Table 2). Height growth after 46 weeks of production was similar for both irrigation practices (Table 3). The change in plant width was lower for plants irrigated with CIRRIG, but this was attributed to an extra shape pruning carried out only in the CIRRIG test zone on day 135. This pruning reduced plant height 4 inches and plant width 14 inches. By day 170, CIRRIG plants had recovered much of the height difference, but width was still 3 inches less than TIP plant width. A subsequent pruning in both irrigation test zones on day 190 removed 7 to 8 inches of plant height and 8 to 10 inches of plant width. Subsequent growth of CIRRIG plants resulted in a final plant height like TIP, but plant width remained 2 inches smaller. Although CIRRIG plants were not as wide as TIP, the extra pruning gave CIRRIG a denser canopy, which improved plant quality. Similar to the other microirrigation trials, the average LF in M3 was higher than the target for most of the trial (Table 4).

Total irrigation water applied to crape myrtle was reduced by 31% using CIRRIG compared with TIP (Table 2). Only two LF tests gave values below the target of 25%, indicating that CIRRIG was not underwatering for most of the trial. Stem caliper growth was decreased 7% with CIRRIG compared with TIP, but the difference in growth (0.7 mm) was small compared with the variability indicated by the measured standard deviations (Table 3). One lesson we learned regarding this crop is that shoot growth is rapid, and thus the LF testing interval should be shortened to keep up with the changing water needs. Likewise, we think irrigation efficiency using CIRRIG with this crop would improve if LF tests were conducted immediately after pruning to account for reduced rates of ET that result from significant reductions in leaf canopy.

CIRRIG had a greater effect in conserving water while maintaining good growth in microirrigated trials than in sprinkler-irrigated trials. We believe the primary reason is that irrigation application rates are considerably lower for sprinkler-irrigated crops (e.g., 0.4–0.5 inch/h) than for microirrigation (e.g., 6–16 inches/h for a 17-inch-diameter container). Therefore, small changes in microirrigation run times result in large changes in irrigation water applied. We could show HN that the ability of CIRRIG-PLC technology to irrigate with a resolution of seconds instead of minutes was necessary if irrigation efficiency as indicated by LF testing was going to be achieved.

For sprinkler irrigation, we found that TIP was not overwatering crops and may have in fact been underwatering some crops as observed in S3. When we first approached HN about cooperating in this study, we were surprised to see the detail they used in sampling substrate moisture to make regular adjustments in run time as little as 5 min with sprinkler-irrigated crops. We observed early on that we were likely not going to help HN conserve water in their sprinkler-irrigated crops. Although HN also sampled and rated substrate moisture in microirrigated crops, the distribution of moisture in large, microirrigated containers typically is less uniform than the moisture distribution observed for small, sprinkler-irrigated containers. The distribution of substrate moisture in large containers is affected by the spray pattern as well as the substrate depth so that core sampling for substrate rating may be variable. Besides being a problem for TIP, poor distribution of applied water in large, microirrigated containers also leads to uncertainty with LF testing. Irrigation run time adjustment based solely on a LF test assumes 100% retention of water before significant leaching occurs. This assumption is likely not valid with high flow emitters in large containers. On the basis of this study and experiences in other nurseries, we believe that setting a low LF target (e.g., 10% to 20%) may not provide a sustainable amount of water for a LF-driven microirrigation scheduling program such as CIRRIG. The best target LF will depend on several factors, such as the substrate's physical properties, the irrigation system type, delivery rate and reliability, plant species, and stage of crop production. Currently, we are suggesting a target LF of 25% to 30% for microirrigated crops in commercial settings. For sprinkler irrigation, we believe a 10% to 15% LF target gives good results for nurseries such as HN that have a sprinkler irrigation system that delivers water uniformly (DU > 80%). We hope future research will help better define ideal target LF values to use in container nurseries.

Potential water savings from using CIRRIG at HN can be estimated. If it is assumed that CIRRIG was not overwatering S3 so that results from this trial are not used, then CIRRIG saved little or no water compared with TIP in sprinkler-irrigated areas. For microirrigated areas, the average water savings for the four trials weighted by the number of days in the trial was 1270 gal/acre per day or 464,000 gal/acre per year. HN's pumping cost based on electric bills and flowmeter readings at each of their two pumps was $0.20/1000 gal. Using this cost rate, potential pumping cost savings for 35 acres in microirrigation would be $3250 per year, which is equivalent to only $0.03 per container at a plant density of 3000 containers per acre. Clearly, there is little monetary incentive to conserve water with CIRRIG when each plant in a trade 15-gal container is selling for $45 to $65.

For HN, potential pumping cost savings using CIRRIG were not as important as the potential labor cost savings of substituting a LF testing program for the traditional substrate moisture sampling practice. HN staff estimated that implementing an automated CIRRIG system including an LF testing program in their nursery will save them $35,000 to $40,000 per year in labor alone. This savings was the labor associated with reducing the irrigation staff from three persons to two. HN's traditional irrigation management entailed three staff sampling substrate, making ratings, meeting as group to decide irrigation changes, and implementing changes in manual time clocks for 156 valves two to three times per week. Additional irrigation activities included routine irrigation system checks and repairs. We asked the staff to monitor time required for conducting LF tests relative to the time spent with their traditional method of sampling and rating soil moisture. During a 3-week period, TIP took 32 min per valve, whereas LF testing took 23 min per valve. Although only a short observation period, the observed 28% decrease in fieldwork did support the estimated reduction in irrigation staff from three persons to two. Regardless, our experience is that HN devoted more water management effort than most container nurseries. Therefore, we believe that potential labor savings in most other container nurseries would be less than estimated by HN.

Toward the end of our cooperative project with HN, the nursery decided to install PLCs to control all 156 valves for their 70 acres of production area. The hardware cost for installing the system at two pump locations was $8000 and included two weather stations ($2700), two router/USB cell modems ($850), two microprocessors ($150), six PLCs ($3800), and miscellaneous wires, cables, and other electronic accessories ($500). This is a new technology that to date has been supported with research funding, and thus we are unsure how the CIRRIG system and service will be monetarily supported in the future. Our best estimate is that a contract for service would be entered between the nursery and the university that would initially include installation of hardware (provided by nursery), training and service at $10,000 per year and decrease over time. Training would entail 1) how to conduct a LF testing program, 2) how to enter LF results and manage the CIRRIG program, and 3) how to monitor irrigation through the PLC software. Our experience is that the average irrigation worker would have little trouble learning these three aspects of the automated CIRRIG system.

Other precision irrigation technologies have also shown benefits in saving water and management costs in a commercial nursery. Belayneh et al. (2013) reported that irrigating two tree crops with an automated substrate moisture-sensing system resulted in water savings of 63% and 36% when compared with the nursery's traditional irrigation practice of manually changing irrigation rates once or twice per week. The estimated cost of the sensor-based system at a 175-acre nursery was estimated at $15,000 per year, which was comparable to the cost we estimated for installing a CIRRIG system at HN. The nursery's reported pumping cost savings with sensor-based irrigation after adjusting to a $0.20 per 1000 gal pumping cost rate and a 70-acre production area was $3830 per year, greater than the $3250 year savings we estimated for HN. As we report for HN, the automated, sensor-based irrigation system also reduced estimated management costs. Management savings with their sensor-based system were estimated at $12,200 per year compared with the estimated labor savings of $35,000 to $40,000 using CIRRIG at HN. Clearly, precision automation irrigation technologies, regardless of the system, have the potential to decrease labor cost in addition to water use. Our experience is that each nursery is unique regarding its potential use of precision irrigation technologies. Having several options such as a sensor-based system or weather-based LF system should help the industry move toward using irrigation systems that objectively evaluate irrigation needs. On the basis of the few reported on-farm studies, labor savings may prove to be a greater driving force for change than water savings.

Making a significant change in an irrigation practice is no easy task for a nursery. We believe that directly working with staff during this 2-year project was crucial for the nursery to be able to evaluate how the CIRRIG technology would work specifically at HN. The visual nature of the LF test was an important attribute that helped staff appreciate how LF testing could provide an alternative indication of irrigation efficiency. For HN, using LF testing in lieu of substrate moisture sampling would save the nursery significant labor regardless of whether an automated system such as the CIRRIG-PLC tested was used or not. Although there is some doubt regarding weather adjustment in irrigation rate using CIRRIG improves irrigation efficiency over a fixed schedule based on routine LF testing, HN valued the added benefits that the CIRRIG-PLC system provided regarding zone management and record-keeping as well as real-time irrigation control and weather monitoring, both locally and remotely.

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