Use of a Bulk Soil Capacitance Sensor in Small Containers To Control Irrigation in a Greenhouse

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Abstract

Automating greenhouse irrigation based on growing medium water content measured by sensors, instead of a tactile, timing, or weighing method, has been done with large containers. Using sensors with small containers (e.g., 10 in^3 [164 cm^3]) commonly used in forest and native plant nurseries, however, has not been done. We tested the EC-5 sensor (METER Group, Pullman, WA) by examining calibration relationships for small containers as they dried from container capacity. These relationships were highly significant down to 63 percent saturation. Three sensors were then used to control irrigation for 90 days. One sensor drifted approximately 10 percent, and the other two were stable. Repositioning two sensors resulted in no change for one and an increase of 10 percent for the other. These sensors have potential for automating irrigation in small containers provided they are calibrated, tracked for sensor drift, and recalibrated after repositioning. This paper was presented at the Joint Annual Meeting of the Northeast Forest and Conservation Association, the Southern Forest Nursery Association, and the Intertribal Nursery Council (Walker, MN, July 31 to August 3, 2017).

Introduction

Irrigation control is a crucial part of greenhouse operations (Dumroese and Haase 2018, Landis and Wilkinson 2009). If too little water is available, the plants may grow slowly or even die if the irrigation system is turned off or fails (Landis and Wilkinson 2009). If too much water is present, the plants are susceptible to root disease or can become hypoxic, each of which contributes to growth problems or mortality (Klaring and Zude 2009, Landis and Wilkinson 2009).

Implementing a quality irrigation method to satisfy plant needs can be done several ways. Monitoring to determine when to irrigate can be done manually by inspecting plant condition, lifting containers to feel if they are lighter, or by weighing containers (Dumroese et al. 2015, Landis and Wilkinson 2009). Automated weighing methods are another option and can be more efficient than manually weighing containers (Walters 1977). Recently, automation using load cells to weigh containers has been demonstrated (Girard and Gagnon 2016). This approach has drawbacks, however, because plants gain mass as they grow, thereby necessitating container capacity recalibration, and load cells can have significant thermal drift needing correction (Girard and Gagnon 2016). Using soil moisture sensors is another automated monitoring method that avoids some of those drawbacks (Nemali and van Iersel 2006).

In recent work, irrigation control has been implemented using a variety of sensors to determine media moisture content (Lea-Cox 2012), which are then used to activate irrigation systems when reaching a target water content. The sensor discussed in this article is the ECH20 EC-5 (METER Group, Inc., Pullman, WA). This sensor and similar sensors work well in soilless substrates commonly used in greenhouse and nursery settings (Hoskins et al. 2012, Lea-Cox 2012, Nemali and van Iersel 2006). These sensors were designed for bulk soil applications in field settings and are also used to control irrigation in agricultural fields (Kim et al. 2008). As such, they also work well in relatively large (> 4 gal [17.5 L]) containers (Girard and Gagnon 2016). Functionality in large containers has been recognized for many nursery and greenhouse applications, but less work has been performed using smaller containers (e.g., 10 in^3 [164 cm^3]). Girard and Gagnon (2016) indicated that the EC-5 sensor, which has a measurement volume of 14.6 in^3 (240 cm^3) (Cobos

2015), would not be adequate for small containers (3 to 21.4 in^3 [50 to 350 cm^3]) commonly used in forest (Girard and Gagnon 2016) and native plant nurseries (Stuewe 2018). With a measurement volume larger than some small containers, the concern is that the sensor would be measuring more than media moisture (e.g., air or materials surrounding the small container). We argue the sensor may be adequate, however, because the measurement volume is strongly weighted toward the sensor surface (Cobos 2015).

In this study, we tested the hypothesis that the EC-5 sensor could accurately determine medium moisture content in small (10 in^3 [164 cm^3]) containers and be useful as a signal for computer-controlled greenhouse irrigation systems. This method enables irrigation to be controlled based on mass loss from 100 percent saturation (i.e., container capacity) to differing target desiccation levels used at various growth stages (Landis 1989). The technique will allow for automated irrigation without weighing racks of containers by hand other than for calibration.

Materials and Methods

We conducted this study at the greenhouse facility of the Confederated Tribes of the Umatilla Indian Reservation (CTUIR) Science and Engineering Laboratory (Pendleton, OR). The greenhouse was designed to use 10 independent irrigation-controlled sectors. Each sector holds 32 1- by 2-ft (30.5- by 61-cm) trays, each of which holds 98 10-in^3 (164-cm^3) containers (Ray Leach Cone-tainers, Stuewe & Sons, Inc., Tangent, OR) that have a 1.5-in (3.8-cm) diameter and 8.3-in (21.0-cm) depth. All plants were kept on benches that are about 3.5 ft (1.1 m) high.

Irrigation and Sensor Control System

The irrigation system (figure 1) is similar to that described in Nemali and van Iersel (2006). The EC-5 sensors were connected to a multiplexer (AM16/32B, Campbell Scientific, Logan, UT), which was connected to a datalogger (CR10X, Campbell Scientific, Logan, UT) to measure the sensor response. The datalogger was programmed to measure the EC-5 response once every minute. Medium temperature was measured in the same container as the EC-5 sensor and used to describe drying patterns during hot and cool periods. Temperature was measured with Type-T copper-constantan thermocouples that were connected to the multiplexer. The EC-5 sensor has a minor response to temperature, and such effects were ignored (Nemali and van Iersel 2006).

Irrigation was controlled using 10 solenoid valves (one for each sector) (264-06-03, The Toro Company, Riverside, CA) connected to a 16-port relay driver (SDM-CD16 AC/DC controller, Campbell Sci.) (figure 1). The solenoids were supplied with pressure-controlled water (40 to 60 psi), which was routed to each sector with flexible 0.5-in (1.3-cm) black plastic tubing. Irrigation water was emitted at a rate of 1.3 gal per min (5 L per min) from each mister located about every 24 in (61 cm) along the tubing. Each mister was about 12 in (30 cm) below the tubing at the end of 0.25-in (0.64-cm) diameter black plastic tubing. Two irrigation lines are along and above each table. The misters are suspended approximately 27 in (69 cm) above the top of the containers.

The containers were periodically watered manually by turning solenoid switches on and off. In addition, manual watering was done to fertilize, water newly transplanted seedlings, or test the system. Each liquid fertilization event was done for 36 minutes using the irrigation system.

Sensor Placement and Calibration

Each sensor, along with a thermocouple, was placed near the center of a container in a full rack (figure 2a). To facilitate sensor placement, a screwdriver was used to create an opening in the medium (figure 2b). The sensor was then carefully pushed into the container until the top of the sensor was below the media surface (figure 2c). The medium was then pushed down around the sensor to eliminate air spaces at the sensor surface. Medium was added to the surface to ensure that the sensor body was covered (figure 2d). The medium used was Sun Gro SS LA4 RSI Potting Soil (Sun Gro Horticulture Distribution Inc., Agawam, MA), which is composed of 65 percent peat and 35 percent pumice and perlite.

Six sensors were used to examine regression relationships for a variety of species and plant sizes between sensor signal (mV) and percent saturation of racks as they dried between 31 May and 8 June 2017. Three racks next to the rack with a sensor were used for mass determination. The six sets of racks and sensors were

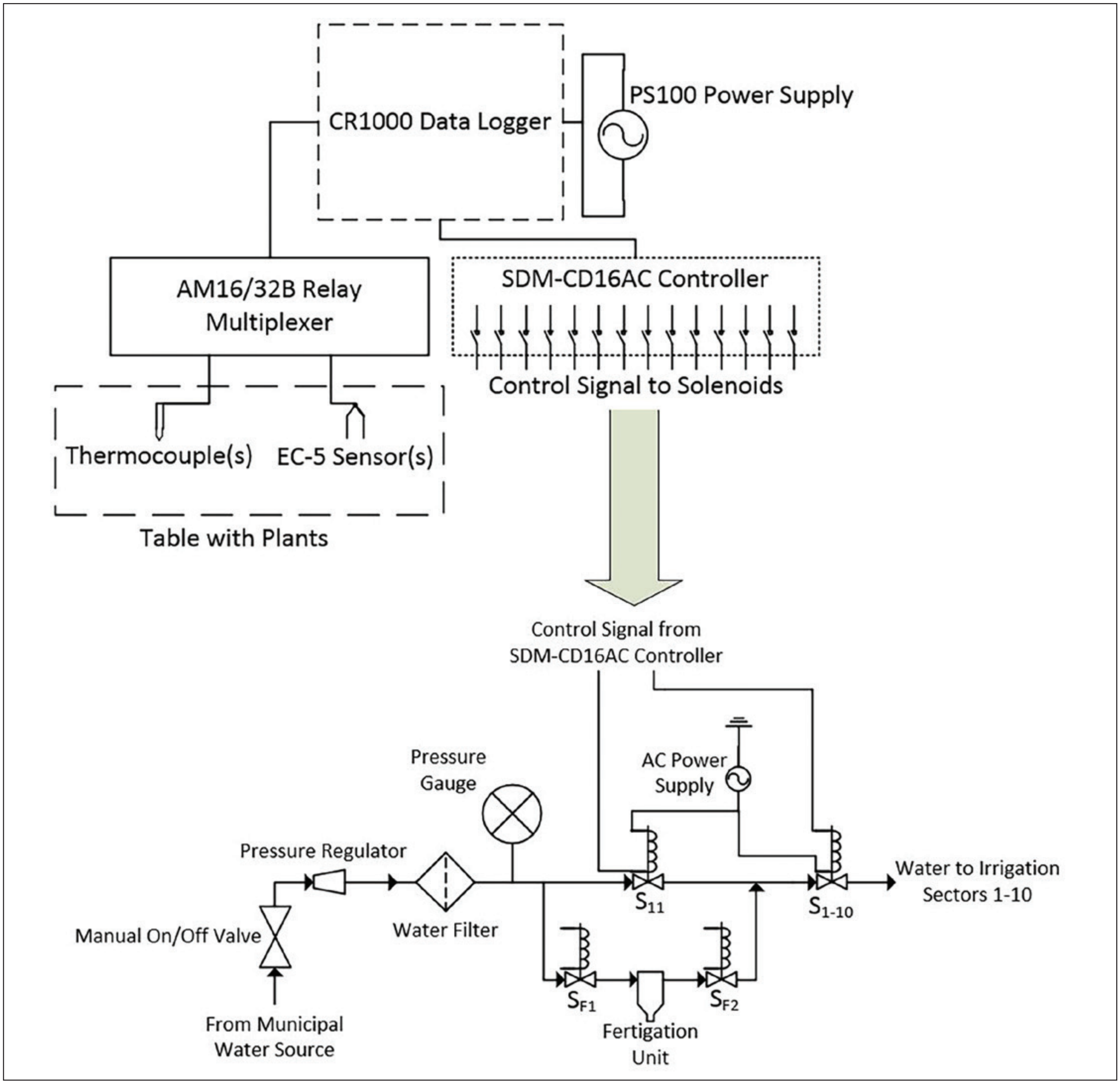

Figure 1. Schematic of the irrigation control system. The greenhouse has 10 sectors that can be independently controlled. Each sector has two tables with plants.

on separate tables in the greenhouse. The racks were irrigated until supersaturated and allowed to drain. The initial measurements (100 percent saturated, container capacity) were recorded when the racks first stopped draining. Rack mass was determined on a platform scale (ULINE H-794, Pleasant Prairie, WI) (figure 3). Mass was measured eight times as the racks dried over several days. The sensor signal was recorded immediately after the mass of each of the three racks was determined for each sensor.

A second-order polynomial linear regression was used to relate percent saturation data to the sensor signal (mV) as—

Equation 1: Percent saturation = 100(rack mass/saturated rack mass) = $b_0 + b_1 mV + b_2(mV\text{-}mV_{ave})^2$

where the bi values are estimated linear regression parameters, and mVave is the average of all mV values of the calibration dataset for each sensor. The formula for converting the factory-supplied response

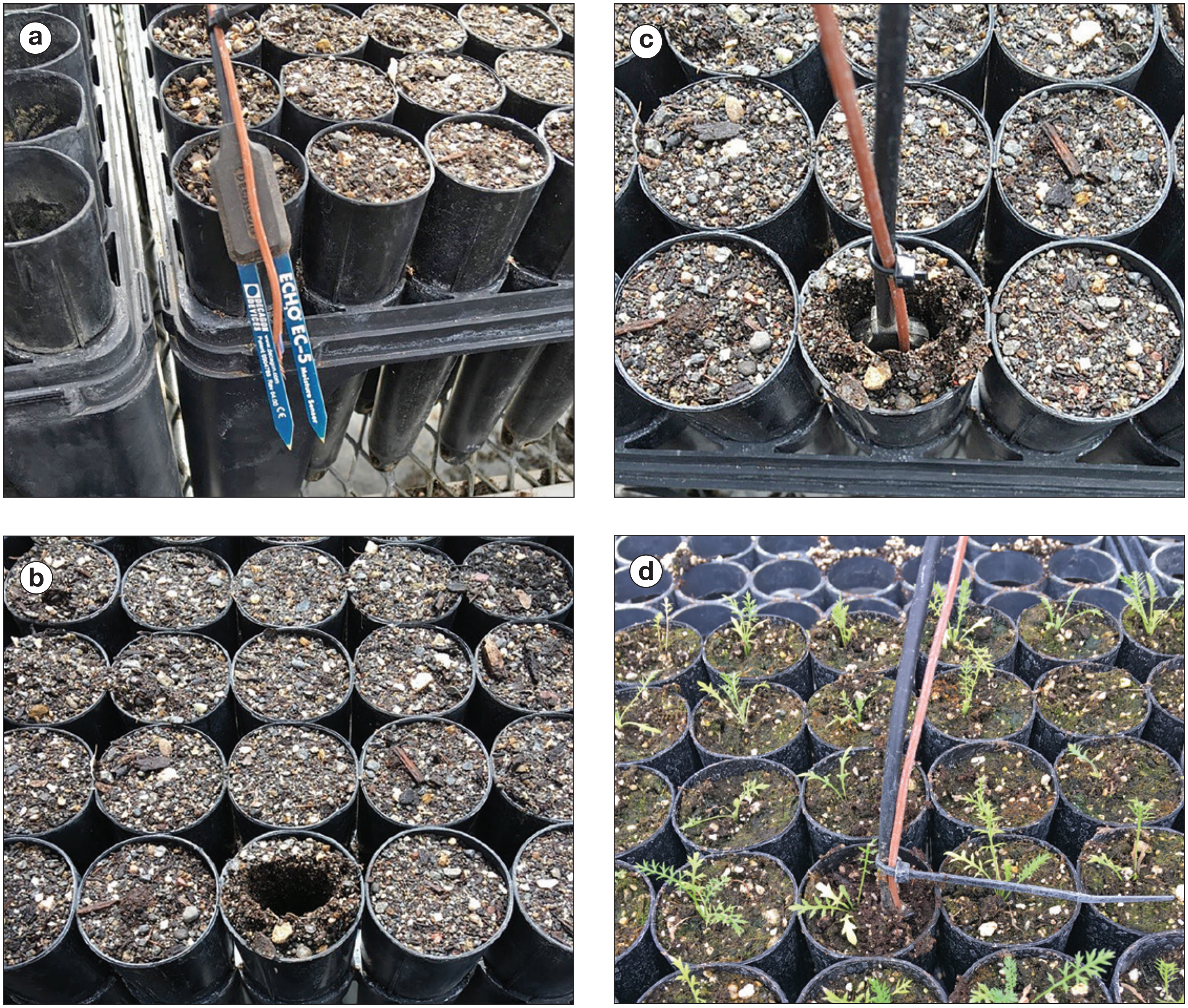

Figure 2. (a) The EC-5 sensor and the Type-T thermocouple used to collect data from small containers in racks. First, (b) an opening was made in the container medium for (c) sensor insertion. After insertion, (d) the medium was filled in around the sensors. (Photos by Steven Link, 2017)

Figure 3. Rack of 98 common yarrow (*Achillea millifolium* L.) seedlings being weighed on the ULINE scale. (Photo by Steven Link, 2017)

variable, volumetric water content (VWC), to mV for the EC-5 sensor was provided by the METER Group (Decagon Devices 2016) and is mV = (VWC + 0.4)/0.00119.

System Evaluation

Three EC-5 sensors were used to test if they would provide a useful control signal for a computer-controlled greenhouse irrigation system. Each EC-5 sensor was used to control a separate section of the greenhouse. Two color-coded sensors were calibrated and used with small *Achillea millifolium* L. (common yarrow) seedlings (red and blue sensors), and a third sensor was calibrated only with medium, then transferred to a container with a larger common yarrow seedling (black sensor). Two thermocouples (one thermocouple associated with the red sensor failed) were used, and the average of their data was used to examine medium temperature patterns. The red and blue sensors were moved to similar pots with small yarrow on day 30 of the evaluation to assess the consequences of sensor movement. Data were recorded from 19 June to 25 September 2017.

The data acquisition and control program was written with CRBasic software (Campbell Scientific). This system turned on irrigation when a prescribed set point was reached. In this case, the set point was a sensor-derived, percent saturation water content. Therefore, when the percent saturation water content dropped to a prescribed value, as measured by a sensor, the relay driver for a solenoid was activated and irrigation occurred. Irrigation continued for 20 minutes to ensure containers were fully saturated and a small amount of water leached from the bottoms of the containers (as discussed in Landis and Wilkinson 2009). Set points were initially at 90 percent and reduced to 85 percent after 15 days. Irrigation intervals varied from 1 to 12 days depending on the sensor.

Signal Stability Evaluation

Sensor stability through a 97-day test period was evaluated. Signal drift was assessed by relating the computed percent saturation value at container capacity to time from day 13, when the 85 percent set point was initiated, to the end of the observation period. The linear regression used was—

Equation 2: Mean percent saturation = $b_0 + b_1{*}t$

where t is time (days) and b_0 and b_1 are estimated parameters.

The effect of moving sensors was assessed by comparing computed percent saturation at container capacity for the period between initiation of the 85 percent control level and the day of movement with container capacity values until the end of the observation period.

Data Analysis

Data from each sensor were analyzed separately using JMP software (SAS Institute 2012) and SigmaPlot 13.0 (Systat Software, Inc., San Jose, CA). Error terms are one standard error of the mean (one SE). Statistical significance is set at $\alpha = 0.05$. Sensor data were analyzed to determine if significant regression relationships were present, as determined by Equation 1, and if any significant sensor drift occurred, as determined by Equation 2. The effect of moving sensors was tested using Student's t-test.

Results

Sensor Calibration

All sensors were highly sensitive to changes in percent saturation (figure 4). The green sensor was responsive, down to about 63 percent saturation, the lowest percent saturation of all rack sets. The regression relationships between percent saturation and sensor signal were highly significant, with greater than 98 percent of the variation explained for all sensors (table 1).

Irrigation Control—Black Sensor

Control of the sector of the greenhouse with the black EC-5 sensor was started on day 8, with irrigation initiated at 90 percent saturation and lowered to 85 percent saturation on day 15 (figure 5a). Any value of

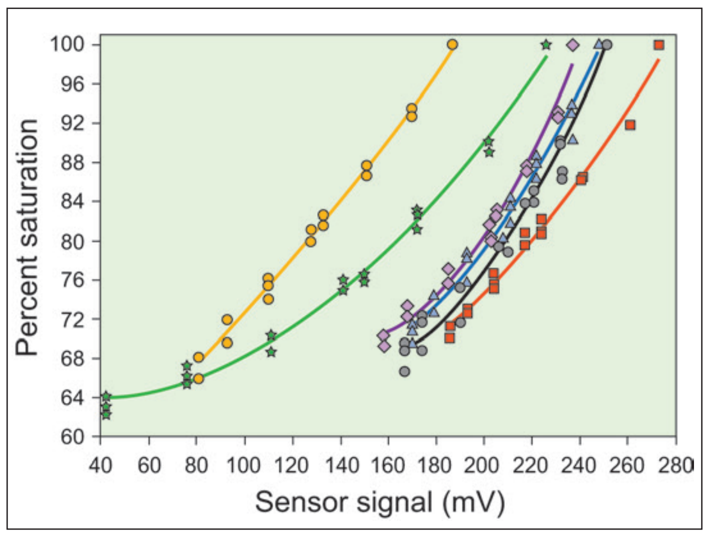

Figure 4. Individual calibration curves for six EC-5 sensors. For each curve, three adjacent racks were weighed from saturation through drying down, on eight measurement dates (some data points overlap and are not visible). Sensors are color coded and were placed in containers with the following plant species and stem heights: yellow, 2.4 in (6 cm), *Achillea millifolium* L. (common yarrow); green, 5.9 in (15 cm), *Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young (Wyoming big sagebrush); pink, 2.2 in (5.5 cm), *Chrysothamnus viscidiflorus* (Hook.) Nutt. (yellow rabbitbrush); blue, 1.6 in (4 cm), common yarrow; black, container medium with no plant; and red 0.8 in (2 cm), common yarrow.

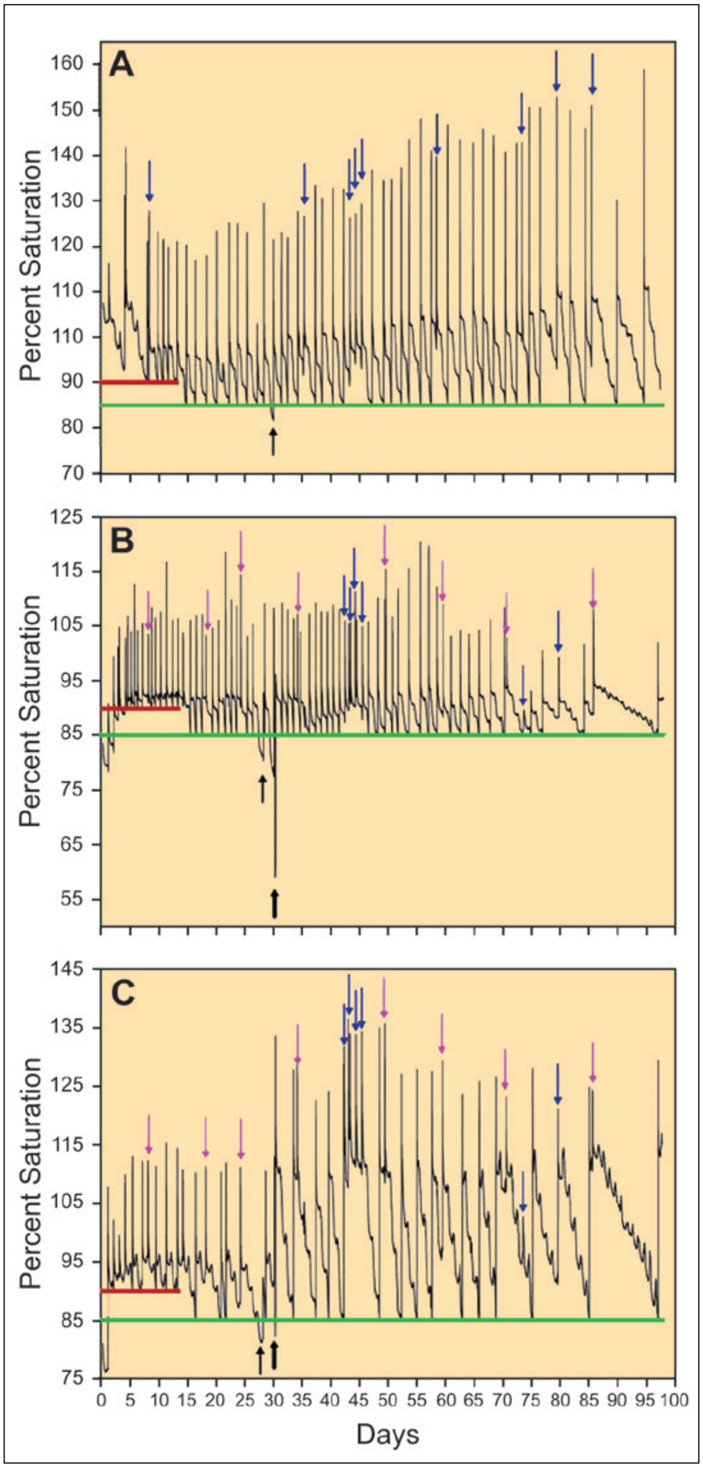

Figure 5. Percent saturation of containers controlled with the EC-5 sensors (a) black, (b) red, and (c) blue. The red line indicates control at 90 percent saturation starting on day (a) 8, (b) 5, and (c) 6, and the green line is control at 85 percent saturation. The blue arrows pointing down indicate manual irrigation. The thin black arrow pointing up indicates a time when the water system had been accidently shut off. The pink arrows pointing down indicate liquid fertilization application. The (a) blue sensor had been removed from bare soil and placed in a container with a larger common yarrow plant at the beginning of the observation period. The (b and c) thick black arrows pointing up indicate sensor removal and placement in a new container

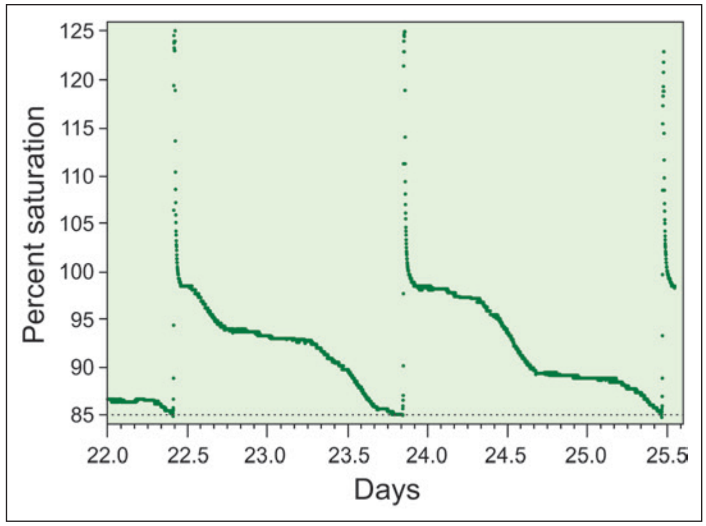

Figure 6. Black sensor data showing fine scale characterization of irrigation initiating at 85 percent saturation for three periods in figure 5a.

more than 100 percent is an extrapolation given that the calibration was done for values less than or equal to 100 percent saturation. Containers with values of more than 100 percent saturation are supersaturated and will rapidly drain. The end of drainage can be noted when the decrease in percent saturation slows (figure 6). Manual watering events are visible in the data trends where irrigation was initiated before the set point was reached and are noted with downward pointing blue arrows (figure 5a). The black arrow pointing up indicates an event when the water system had been accidently shut off. This sensor had a significant (Equation 2, $p < 0.0001$) and increasing linear drift ($b_1 = 0.18 \pm 0.02$, $n = 46$) in percent saturation after irrigation events from day 13 to the end of the observation period. The rate of drying slowed beyond day 85 when temperatures were cooler (figure 7), resulting in longer intervals between irrigations.

A close examination of percent saturation dynamics during approximately 3 days shows that water loss slows at night and increases during the day (figure 6). The rate of increase and decrease in percent water content is very high when the irrigation system turns on at 85 percent saturation and while the containers drain (figure 6).

Irrigation Control—Red Sensor

Control of the portion of the greenhouse with the red EC-5 sensor began on day 5 with irrigation initiated at 90 percent saturation (figure 5b). This sensor was removed and placed in similar cone on day 30. The

Table 1. Second-order polynomial regression relationships between percent saturation weights and signals for the six color-coded sensors. For each sensor, three adjacent container racks were used to generate weight data.

Sensor	$b_0 \pm 1$ SE	$b_1 \pm 1$ SE	$b_2 \pm 1$ SE	R^2	p-value
Yellow	42.1 ± 0.655	0.300 ± 0.00480	0.000480 ± 0.000152	0.99	< 0.0001
Green	46.6 ± 0.609	0.201 ± 0.00355	0.000912 ± 0.0000614	0.99	< 0.0001
Pink	6.68 ± 2.10	0.368 ± 0.0100	0.00304 ± 0.000426	0.98	< 0.0001
Blue	7.90 ± 2.30	0.357 ± 0.0109	0.00171 ± 0.000462	0.98	< 0.0001
Black	5.37 ± 2.07	0.357 ± 0.010	0.00255 ± 0.000380	0.98	< 0.0001
Red	13.2 ± 1.80	0.304 ± 0.00827	0.00102 ± 0.000317	0.99	< 0.0001

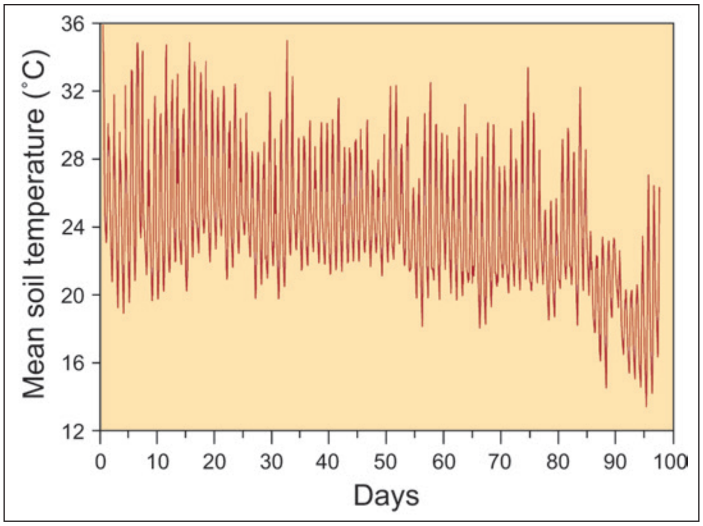

Figure 7. Mean (n = 2) container media temperature dynamics of the black and blue sensors.

movement of the sensor did not result in a significant ($p < 0.9159$) change in percent saturation. Values were 90.9 ± 0.38 percent (n = 14) before the move and 90.9 ± 0.24 percent (n = 37) after the move. This sensor did not have a significant (Equation 2, p = 0.0893) linear drift ($b_1 = -0.017 \pm 0.01$, n = 51) in percent saturation from day 15 to the end of the observation period. Similar to the black sensor, irrigation intervals increased when temperatures decreased (figure 7).

Irrigation Control—Blue Sensor

The portion of the greenhouse controlled with the blue EC-5 sensor began on day 6 with irrigation initiated at 90 percent saturation (figure 5c) as with the other sensors. The events noted by the arrows in figure 5c are the same as in figure 5b. This sensor was also removed and replaced on day 30. The movement of the sensor resulted in a significant ($p < 0.0001$) step change in percent saturation from 94 ± 0.99 (n = 7) before the move to 110 ± 0.52 (n = 25) after the move. This sensor did not have a significant (Equation 2, p = 0.4605) linear drift (b1 = -0.025 ± 0.033, n = 25) in percent saturation from day 30 to the end of the observation period. Similar to the other sensors, the rate of drying slowed beyond day 85, when temperatures became cooler (figure 7).

Discussion

The regression method was designed to predict percent saturation of growing medium using EC-5 sensors placed in racks of plants as they dry in a greenhouse setting. Monitoring medium moisture is an effective tool for irrigation scheduling (Landis 1989, Landis and Wilkinson 2009). Sources of error with this approach include difficulty in accurately determining when racks had stopped draining at the fully saturated condition. As racks drained, the drain rate decreased until it appeared that it had stopped. Moving the fully saturated rack to the scale resulted in additional water loss from the containers. This loss was difficult to control but is not likely a significant source of variation. For instance, if one drop (0.018 oz [0.5 g]) fell out of each container during the weighing process, then the mass lost would be 98 × 0.018 oz or 0.17 oz (4.9 g). The typical mass of a saturated rack of containers was about 31 lb (14 kg), thus this potential source of error is only 0.035 percent and is not significant.

The largest source of variation among the six sensors and their associated racks was likely how the sensor was placed in the media and the level of homogeneity of the container mix at the sensor interface (van Iersel et al. 2013). Variation among sensors is very low when compared under similar conditions (Campbell et al. 2009). In our study, the range among the sensors at 100 percent saturation was 100 mV, or 37 percent of the highest reading. Campbell et al. (2009) noted this high variation in container media, and attributed it, in part, to variation in container media density and associated variance in the amount of media or air at the sensor interface (van Iersel et al. 2013). Such variability was also noted in van Iersel et al. (2013) who concluded that calibration was advised when using soilless and highly porous substrates common in the horticulture industry. In the current study, no special effort was made to carefully make media homogenous, as they are not likely to be very homogeneous in working greenhouses. Even though sensor calibrations were highly variable, we can conclude that the EC-5 sensor will adequately determine media moisture content in small (10 in^3 [164 cm^3]) containers and serve as a control signal for computer-controlled irrigation systems.

Irrigation patterns demonstrated classical diurnal dynamics when examined closely during a 3-day period with slow evaporative water loss at night and rapid water loss during the day when evapotranspiration is high (van Iersel et al. 2013). Fine definition of patterns can be achieved using 1-minute acquisition of data and is easily done with current computers and data acquisition systems. In contrast, Nemali and van Iersel (2006) acquired data only every 20 or 60 minutes. Rapid data acquisition is useful when alarm systems are used to detect failures such as water system breaks and when it is important to detect rapid responses in plant water use, such as when large plants are in small containers (van Iersel et al. 2013).

The EC-5 sensor generated meaningful data during the entire observation period, indicating that it can function for extended periods. Our observation period was more than two times as long as that in Nemali and van Iersel (2006), who concluded that a similar EC sensor (ECH2O-10) was stable. Others have also noted the stability of the sensor (Campbell et al. 2009). One of our sensors drifted, however, and the other two were stable during the observation period. The sensor that drifted (black) was calibrated in media and placed in a container with a large common yarrow plant, and the other two sensors were placed in containers with small common yarrow. It may be possible that variations in root density may affect sensor stability over time, although Nemali and van Iersel (2006) noted that the ECH2O-10 sensor was not sensitive to plant size.

Conclusions

We found the EC-5 to be useful in smaller containers (10 in3 [164 cm^3]) for monitoring growing medium moisture content and controlling irrigation in a greenhouse setting. The sensor was sensitive to greenhouse conditions and adjusted irrigation frequency accordingly. Using sensors means that weighing racks of containers would be needed only during sensor calibration. To use the sensors successfully, however, it's important to calibrate, track sensor drift, and be aware of the sensor's sensitivity to repositioning. The rough cost of purchasing and installing the sensors and control system for the Confederated Tribes of the Umatilla Indian Reservation facility was $7,000 (USD). Savings in labor to manually weigh racks to determine water content is expected to recapture this expense. For example, if 1 hour were required per day to weigh racks and the average labor cost is $20.00 per hour, then the investment is recouped in 350 days. The automated system has the additional advantage that it monitors water content 24 hours a day and 7 days a week, which reduces the necessity for scheduling workers on weekends and holidays.

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