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An automated system for controlling drought stress and irrigation in potted plants

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Abstract

Efficient, automated irrigation systems, which can irrigate the substrate of potted plants to a desired level and supply those plants with just the amount of water required for normal plant growth are currently not available. These systems, if developed, could reduce wastage of irrigation water due to excess application. This subsequently could reduce leaching and run-off, and aid growers to cope with increasing regulations of water-use by state governments in the US. Here we describe an irrigation controller that irrigates a substrate to a set-point (volumetric water content, θ) and maintains θ close to that set-point for several weeks. The controller uses calibrated, dielectric moisture sensors, interfaced with a datalogger and solenoid valves, to measure the θ of the substrate every 20 min. When the θ of the substrate drops below the set-point, the controller opens a solenoid valve, which results in irrigation. The θ of the substrate is maintained near a constant level as the datalogger is programmed to increase θ by only 2–3% during each irrigation. Using this controller with bedding plants, we were able to maintain four distinct levels of θ for a prolonged period (40 days), regardless of changes in plant size and environmental conditions. The daily average θ maintained was slightly higher (within 2–3% on any particular day) than the set-point. When the θ measured and maintained by the dielectric moisture sensors was tested using measurements with another probe placed in the same container, the θ measured by both probes was found to be similar, indicating that the controller can indeed maintain θ near the target level. This controller may also have applications in stress physiology, since it allows control over the rate at which drought stress is imposed on plants.

Keywords: Automated irrigation control; Bedding plants; ECH_2O dielectric sensor; Evapotranspirational water-use; Greenhouse production; Irrigation system; Leaching

1. Introduction

Increased labor costs, stricter environmental regulations, and increased competition for water resources from urban areas provide strong motivation for greenhouse and nursery growers to opt for more efficient irrigation systems. Benefits of such systems include reductions in both labor costs and water wastage. Overhead irrigation systems like sprinkler-, boom-, and drip-irrigation, and subirrigation systems like ebb-and-flow and flooded floor irrigation are easily automated. Thus, these systems can reduce labor costs related to irrigation, with subirrigation systems having an additional advantage of minimizing leaching losses from the substrate (Elliot, 1990; Yelanich and Biernbaum, 1990; van Iersel, 1996; Morvant et al., 1997; Uva et al., 1998). However, a potential weakness of these automated systems is their inability to irrigate a substrate to a desired moisture level or in the minimal amounts needed for normal growth.

Automated irrigation systems are commonly run by controllers set to a pre-determined irrigation schedule (e.g. to run at a particular time of the day and for a particular duration) and not based on actual measurements of θ. Often, automated systems irrigate the substrate close to saturation regardless of plant water requirement and result in wastage of good quality irrigation water through leaching and run-off. To minimize water wastage from automated irrigation systems, there is a need to develop improved irrigation controllers, which can irrigate the substrate to a desired θ. Such controllers will aid greenhouse growers to comply with stricter government regulations on water-use and fertilizer run-off.

An irrigation controller, which can wet the substrate to a desired level also will be useful in research on plant water relations. The inability to maintain θ at a desired level imposes a limitation in physiological experiments related to studying

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water requirements of plants. To study plant responses to different θ levels, experiments in the field of plant water relations often are conducted by manually maintaining these θ levels. This method commonly involves weighing the containers daily and replenishing the fraction of water lost in transpiration (Sinclair and Ludlow, 1986; Ekanayake et al., 1993; Ray and Sinclair, 1998). This method is labor-intensive and in addition, changes in plant fresh mass are generally neglected in calculations of evapotranspiration. In other studies, to overcome the intensive labor of the previously-described technique, plant responses to substrate water content are studied by withholding irrigation and studying responses as the substrate water content decreases. This also is not an ideal method as the rate at which drought stress develops after withholding water is usually faster in containers (due to the smaller volume of available water) than under natural conditions and is not controlled. Observed physiological responses in plants can be different for a rapidly-imposed and slowly-imposed drought stress (Cornic et al., 1987; Ludlow, 1987; Saccardy et al., 1996; Earl, 2003).

With both methods, it is not possible to have precise control over the rate at which drought stress is imposed (Earl, 2003). Irrigation controllers that allow better control of θ may make it possible to study plant responses at distinct and precisely-controlled levels of θ.

Here, we describe an irrigation controller that can be used to irrigate and maintain substrates close to a desired θ for prolonged periods. Irrigation is controlled by a datalogger, which uses dielectric moisture sensors, a relay driver, and solenoid valves to irrigate and maintain substrates close to a desired level. This system can be used to either control the rate at which drought stress is imposed, or to maintain θ at distinct levels. This system has many potential applications in horticultural production and research.

The objectives of this study were:

(i) to test whether the controller can maintain the θ of substrates at a constant level and close to a set-point for a long period and within an acceptable range of the targeted value,
(ii) to test whether fluctuations in greenhouse environment and variations in plant size affect the performance of the controller to irrigate and maintain substrates close to a desired θ level, and
(iii) to test the accuracy of θ maintained in substrates by the controller.

2. Materials and methods

2.1. Irrigation system

The layout of the irrigation system is shown in Fig. 1. Frequent measurements of the θ of the substrate were accomplished using calibrated [$\ln(\theta) = -6.99 + 16V - 9.9V^2$, $R^2 = 0.91$] dielectric soil moisture sensors (ECH_2O-10 probes, Decagon, Pullman, WA, USA). A total of 16 ECH_2O moisture sensors were used in the study. The ECH_2O moisture sensors were connected in a single-ended fashion to a multiplexer (AM25T, Campbell Sci., Logan, UT, USA), which in turn was connected to a datalogger (CR10X, Campbell Sci.) to measure the sensor output. Type-T thermocouples were used to measure the temperature of the substrate. The thermocouples were connected to the multiplexer as well. The datalogger was programmed to automatically measure ECH_2O probe output once every 20 min, and to calculate and compensate θ for changes in substrate temperature based on a pre-determined relationship between substrate temperature and probe output. The voltage output from the probes increases by 1.88 mV per °C, or approximately 0.002–0.003 $m^3\ m^{-3}$ water content per °C (Nemali and van Iersel, 2006). Here we used a temperature correction of 0.003 $m^3\ m^{-3}\ {}^\circ C^{-1}$. To do this, the difference between the temperature at which the probes were calibrated (23.2 °C) and the measured substrate temperature was calculated. Subsequently, for every °C difference, 0.003 $m^3\ m^{-3}$ was added to (for substrate temperatures <23.2 °C) or subtracted from θ, as calculated from the above calibration equation. Although we used ECH_2O-10 probes, other soil moisture probes could be used as well. Based on preliminary data, suitable probes include ThetaProbes (delta T, Cambridge, UK), ECH_2O-5 and ECH_2O-TE probes (Decagon). These three probes have the advantage that they are less sensitive to substrate EC and temperature, and temperature corrections may not be necessary for these probes (our unpublished results).

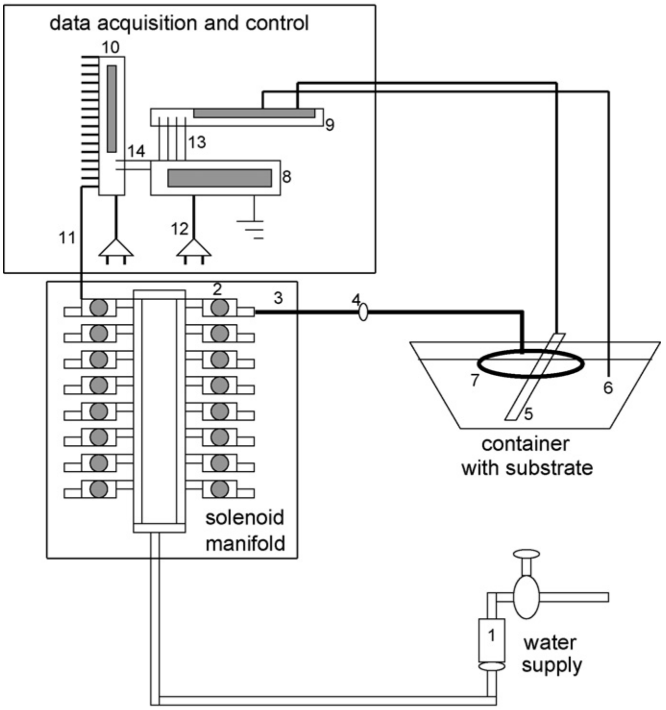

Fig. 1. Schematic diagram showing various parts of the irrigation system. (1) Pressure regulated water source; (2) solenoid valve; (3) outlet tubing; (4) pressure-compensated emitter; (5) ECH_2O sensor; (6) thermocouple; (7) drip emitter (ring); (8) CR10X datalogger; (9) AM25T multiplexer; (10) SDM-16AC/DC controller (relay driver); (11) power supply to solenoids; (12) to main power supply; (13) connecting wires between CR10X and AM25T; (14) connecting wires between CR10X and SDM-16AC/DC controller. Only one container is shown in detail although 16 independent groups of plants can be irrigated.

To control irrigation, 16 solenoid valves (X-13551-72, Dayton Electric Company, Niles, IL, USA), connected to a 16-port relay driver (SDM-CD16 AC/DC controller, Campbell Sci.), were used. Each solenoid and port of the relay driver were related to one of the 16 containers used in the study and irrigated the substrate in the respective containers. The solenoids were constantly supplied with irrigation water from a pressure-regulated water source. In their regular position, the solenoid valves remained closed. When the datalogger measured a lower θ than the set-point in any container, it was programmed to supply power to the valve controlling irrigation to that container. Flexible plastic tubing, connected to the outlet of solenoid valve, supplied water to containers. The volume of water supplied to the substrate during each irrigation was controlled using two pressure-compensated drip emitters (Rain-Bird Irrigation, Tucson, AZ, USA) per container. The drip emitters were connected to 30 cm dribble rings with seven holes (Dramm, Manitowoc, WI, USA). The amount of water supplied to different containers during each irrigation was measured before the experiment (approximately 100 mL/min), and can easily be adjusted by changing the duration of each irrigation event.

The duration of irrigation was controlled by programming the datalogger to supply power to the solenoid valve for a specific period (in this case 1 min) when the ECH_2O moisture sensor measured a lower θ than the set-point. As the datalogger measured θ once every 20 min, there was a period of 19 min for the water to equilibrate in the substrate before the next possible irrigation. The datalogger program used to measure and control θ in up to 16 containers can be downloaded from http://www.hortphys.uga.edu/irrigationcontrol/.

2.2. Methods

To study the first two objectives, data were collected during an experiment conducted with bedding plant species [impatiens (*Impatiens walleriana* Hook. f), petunia (*Petunia × hybrida* Vilm.), salvia (*Salvia splendens* Sellow ex Roemer & J.A. Schultes) and vinca (*Catharanthus roseus* (L.) G. Don)]. In brief, seedlings were grown for 4 weeks from seed in 96-cell plug flats and seedlings belonging to all four species were transplanted (one plant from each species per container) into plastic containers (17.5 L) filled with a soilless substrate [Fafard 2P mix; 60% peat moss and 40% perlite (v/v); Fafard, Anderson, SC, USA]. All four species were grown together in one container to ensure that all species were exposed to the same θ. Approximately 22.5 g of a slow-release fertilizer (Osmocote 14-14-14, Scotts Co., Marysville, OH, USA) was thoroughly mixed with the substrate in each container before transplanting to meet nutrient requirements of the plants during the experiment. Seedlings were irrigated normally ($\theta > 0.4\ \mathrm{m^3\ m^{-3}}$) for a week before subjecting them to water treatments. Treatments comprised of four distinct levels of θ, corresponding to irrigation set points of 0.09, 0.15, 0.22, and 0.32 $\mathrm{m^3\ m^{-3}}$. The two dribble rings were placed on opposite sites in each container to achieve uniform irrigation across the surface of the substrate.

To study the third objective, another experiment was conducted using the same irrigation setup and with substrate (Fafard 2P mix) in 15 cm plastic containers (1.76 L). No plants were used in this study. Two ECH_2O moisture sensors were inserted into each container along with two corresponding thermocouples for temperature compensation of probe output. Similar to the earlier experiment, the datalogger maintained water content in each container based on a set-point using the measurement from one of the two ECH_2O moisture sensors. The datalogger also measured the output of the other ECH_2O moisture sensor. The second ECH_2O moisture sensor was used as a cross-check to test the reliability of θ maintained by the controller using the first ECH_2O moisture sensor. There were four set-points (0.09, 0.15, 0.22, and 0.32 $\mathrm{m^3\ m^{-3}}$) maintained in the substrate during the study. Because no plants were used in this study, water loss form the containers was slow. Thus the interval for θ measurements was changed to 60 min (as opposed to 20 min for objective 1 and 2). The total volume of water supplied in each irrigation was approximately 100 mL.

2.3. Measurements

Two quantum sensors (Apogee Instruments, Logan, UT, USA) and a temperature/RH sensor (HTO-45R, Rotronic Instruments, Huntington, NY, USA) were connected to the datalogger to measure environmental conditions. Environmental data were collected by the datalogger once every 2 min to obtain hourly and daily averages, and daily minimum and maximum values. Daily light integral (DLI, mol $\mathrm{m^{-2}\ day^{-1}}$) was calculated by integrating the photosynthetic photon flux measurements of the quantum sensors throughout each day. Volumetric water content of the substrate was measured by the datalogger once every 20 min (or 60 min in the second study) to obtain hourly and daily averages, and minimum and maximum values during a day. The datalogger also calculated the number of times each container was irrigated, thus allowing for calculation of the total amount of water applied.

Total evapotranspiration (L) from each treatment was estimated from the number of irrigations, θ before imposing treatments ($\theta_{\mathrm{initial}}$), and θ in the substrate at the end of the experiment (θ_{final}):

$$\text{total evapotranspiration} = (\text{number of irrigations} \times 0.1) + (\theta_{\mathrm{initial}} - \theta_{\mathrm{final}}) \times 15,$$

where 0.1 L is the volume of water added in each irrigation and 15 is the volume (L) of the substrate in the containers. Shoot dry mass of the plants in different treatments was determined at the end of the study. Total shoot dry mass from any container was determined by combining the shoots of all plants in a container. Evapotranspirational water-use [volume (mL) of water used per gram of shoot dry matter produced] in the treatments was calculated as the ratio of total evapotranspiration and total shoot dry mass. This equation ignores the shoot dry mass of plants at the start of the study as well as differences in evapotranspirational water-use among species. It is used here solely for illustration purposes.

2.4. Design and analyses

The design was a randomized complete block with four treatments and two replications in both experiments. Experimental units consisted of a single container at any set-point. Variability in actual θ measured between the replications (experiment with plants) is shown as the standard deviation of the mean. Data for shoot dry mass and evapotranspirational water-use were subjected to ANOVA using the general linear models procedure of SAS, version 8.0 (Statistical Analysis Software, SAS systems, Cary, NC, USA). When the ANOVA indicated significant effects, means were separated using Tukey's HSD, with $P < 0.05$ considered to be statistically significant. Significant differences between two ECH_2O probes in any experimental unit in the second experiment were tested using ANOVA.

3. Results and discussion

3.1. Experiment 1

Large variations were seen in the mean DLI and RH inside the greenhouse during the 43 days of the experimental period (study with plants) (Fig. 2). The temperature inside the greenhouse was controlled, hence it did not show large variations during the experiment (Fig. 2). The minimum, maximum, and mean values during the experiment for DLI and RH were 0.44, 11.26, and 4.03 mol m^{-2} day^{-1} and 39%, 91%, and 70%, respectively. Corresponding values for temperature were 18.7, 24.1, and 20.8 °C, respectively. Clearly, large fluctuations occurred in the greenhouse environment (DLI and RH) during this study.

The shoot dry mass differed by up to 250% among the four θ levels maintained in the study (Fig. 3). Shoot dry mass in the 0.22 m^3 m^{-3} treatment was greater than that of the two drier treatments (0.09 and 0.15 m^3 m^{-3}). However, shoot dry mass was not different between the two drier or the two wetter treatments. Thus the θ set points resulted in differences in plant growth and dry mass. The total water volume needed to maintain set-points of 0.09, 0.15, 0.22 and 0.32 m^3 m^{-3} were 1.1, 4.8, 13.6, and 13.7 L, respectively. The similar water volumes in the 0.22 and 0.32 m^3 m^{-3} treatments may seem surprising. Likely, it did not take more water to maintain 0.32 m^3 m^{-3}, because the plants in the 0.22 m^3 m^{-3} treatment were larger and used more water than those in the 0.32 m^3 m^{-3} treatment.

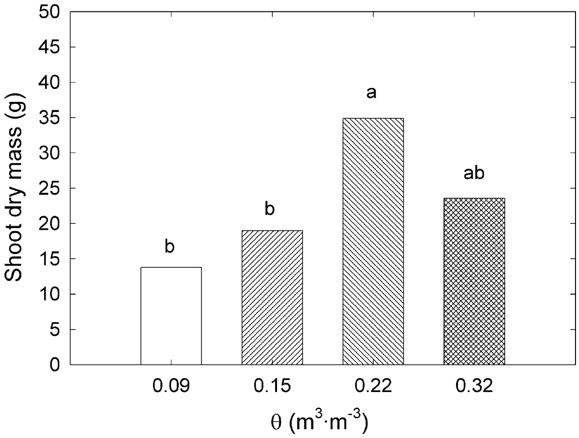

Fig. 3. Mean ($n = 2$) shoot dry mass, combined for four species, at different volumetric substrate water contents (θ) during experiment 1. Mean separation with Tukey's HSD.

Evapotranspirational water-use was different among the driest (0.09 m^3 m^{-3}) and wettest treatment (0.32 m^3 m^{-3}), and increased with increasing θ (Fig. 4). Hence there were differences among treatments in how efficiently the plants used the irrigation water to produce dry mass. This may be caused by differences in water use efficiency (g of dry matter produced per mL of water transpired by the plants) and/or evaporation from the substrate surface among θ treatments.

We were interested to determine whether variations in greenhouse environment, plant size, and water needs of plants grown at different set-points affected the efficacy of the controller to maintain θ slightly above the set-points in different treatments. In the two wetter treatments (0.22 and 0.32 m^3 m^{-3}), the controller started to maintain θ shortly after the start of the experiment. As both of the drier treatments were started at a

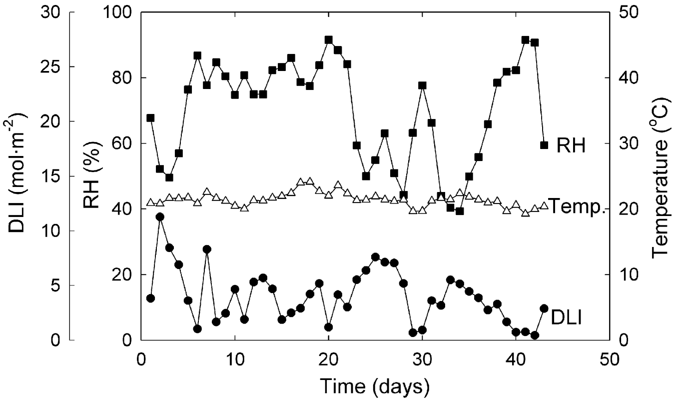

Fig. 2. Changes in daily light integral (DLI), relative humidity (RH), and temperature inside the greenhouse during experiment 1. Data for RH and temperature are daily averages. The different substrate moisture treatments were started on day 0.

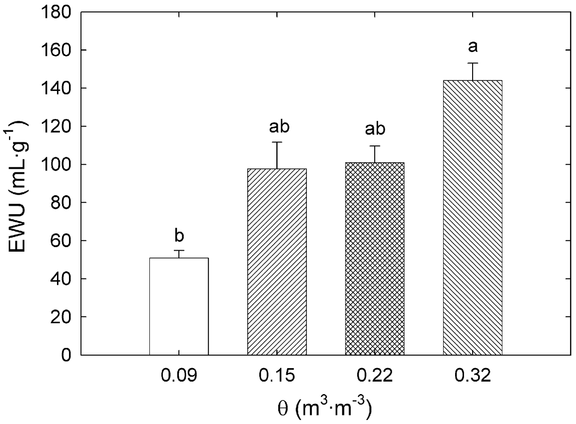

Fig. 4. Mean evapotranspirational water-use (EWU, shoot dry mass/total evapotranspiration) at different volumetric substrate water contents (θ) during experiment 1. Mean separation with Tukey's HSD.

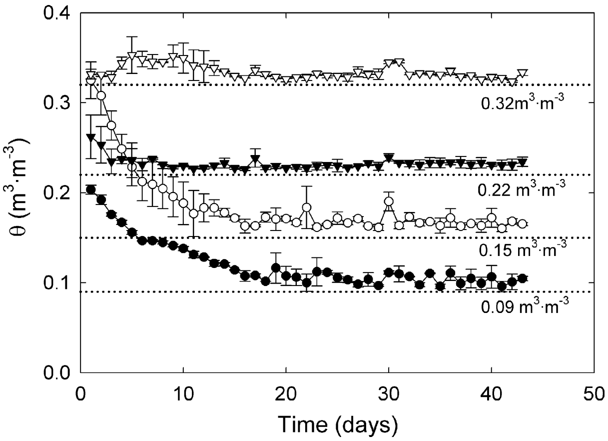

Fig. 5. Mean ($n = 2$) daily volumetric water content of the substrate (θ) maintained in different θ treatments during experiment 1. Error bars represent the S.D. of the mean. The different substrate moisture treatments were started on day 0. The dashed lines indicate irrigation set points.

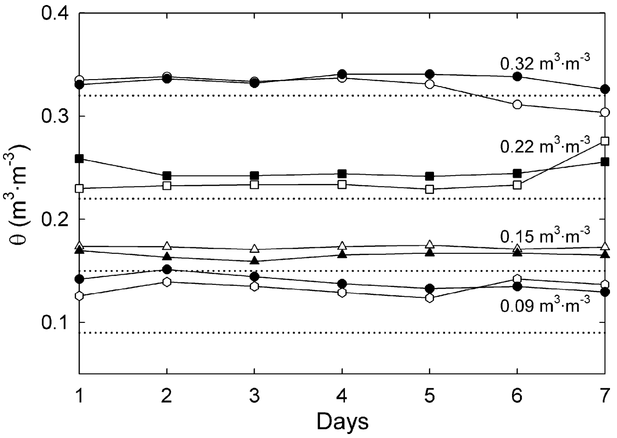

Fig. 6. Average ($n = 2$) daily volumetric water content of the substrate (θ) in different treatments during different days in experiment 2. Closed symbols represent θ measured by the ECH_2O sensor, which was used for irrigation control, while open symbols represent θ measured by a second ECH_2O sensor, which was used for validation purposes. The dashed lines indicate irrigation set points.

higher θ than the target level, it took several days for θ in these treatments to dry down to the target level before the set-point was maintained (Fig. 5). Nonetheless, there were approximately 25 days during which the system maintained θ in the drier treatments. The θ at set-points of 0.09, 0.15, 0.22, and 0.32 $m^3\ m^{-3}$ averaged 0.105, 0.168, 0.231 and 0.331 $m^3\ m^{-3}$ during the last 25 days of the experiment (i.e. the period during which the controller was maintaining θ in all treatments). Thus the daily mean θ was maintained at 0.011–0.018 $m^3\ m^{-3}$ above the set point for irrigation. This difference between the actual θ and the irrigation set point likely can be reduced by applying smaller volumes of water at each irrigation. The daily mean θ was never >0.04 $m^3\ m^{-3}$ higher than the set-point.

The day-to-day variability in daily mean θ was greater in the two drier (0.09 and 0.15 $m^3\ m^{-3}$) than the wetter treatments (Fig. 5). The standard deviation for day-to-day mean θ was 0.058, 0.060, 0.026 and 0.050 $m^3\ m^{-3}$ in the 0.09, 0.15, 0.22, and 0.32 $m^3\ m^{-3}$ treatments, respectively. Peat-based substrates have a lower hydraulic conductivity with decreasing water content (Naasz et al., 2005). It is possible that hydraulic conductivity was low in the two drier treatments, slowing water movement in the substrate, and the applied irrigation water may not have equilibrated evenly throughout the substrate within the 20 min between measurements, resulting in variability in the data. Based on these results, it can be inferred that environmental fluctuations, plant-size, and plant water use had a minimal impact on the performance of the irrigation controller. If it is important to maintain θ closer to the set point, less water could be applied per irrigation, either by decreasing the duration of each irrigation interval, or by using emitters with a lower flow rate. There was practically no leaching up to a θ level of 0.22 $m^3\ m^{-3}$, while only minimal leaching was noticed in the wettest treatment (0.32 $m^3\ m^{-3}$).

3.2. Experiment 2

There were no significant differences between the average θ (pooled across 7 days) measured by both ECH_2O moisture sensors in the same container. In fact, the θ measured by the second ECH_2O moisture sensor closely tracked that of the first ECH_2O sensor (Fig. 6) during different days. Since θ measured by the first ECH_2O moisture sensor in a container was used to maintain θ above the set-points, and this θ was similar to that measured by the second ECH_2O moisture sensor during different days, it can be inferred that the irrigation system accurately maintained θ.

4. Conclusions

Unlike most automated irrigation systems which result in leaching and run-off, our system had little or no wastage of water. The system required little maintenance during the study. Regardless of the time of the day, the system irrigated the plants when the substrate moisture fell below the target level. This irrigation approach can easily be scaled up for use in greenhouses or nurseries, where it would likely result in significant decreases in water use, leaching and run-off. The controller also has potential for use in drought stress studies, since it is possible to control the amount of water available in the substrate (or soil) and thus the level of stress that the plant is exposed to.

The following conclusions can be drawn from this study:

(i) The irrigation system was able to maintain θ for a long period within an acceptable range of the set-point despite large variations in environmental conditions and plant size.
(ii) As opposed to the dry-down or frequent weighing technique for imposing drought stress, this system maintained θ close to the set-point with little or no effect of environment and plant size.
(iii) The validation study confirmed that the θ maintained by the controller was reliable.

We hope that this system can be used as a prototype for future generation automated irrigation controllers to achieve reductions in labor costs and water wastage in greenhouses and nurseries, as well as in stress physiology studies related to substrate–plant–water relations.

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