The Use of Soil Moisture Probes for Improved Uniformity and Irrigation Control in Greenhouses

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Abstract
There is wide variety of soil moisture sensors available for use in greenhouse production and research applications. Such sensors can play a valuable role in improving uniformity of substrate water content in greenhouses, as well as in automating irrigation based on plant water use. Quantification of spatial variability can be used to improve the design of irrigation systems to better match plant water use. The use of soil moisture sensors for irrigation control is promising, because it can greatly reduce temporal variability in substrate water content by watering based on actual crop water use. This not only results in better temporal uniformity, but can also greatly reduce water use. Understanding the spatial distribution of substrate water content and root water uptake within a container is important in determining the optimal sensor location within a container. At the same time, the properties of different sensors need to be considered when choosing the optimal sensor for a particular application. In small containers, it may be possible to measure most of the substrate with a single sensor, while in larger containers sensors ideally would be placed in that part of the substrate where most of the water uptake occurs.

INTRODUCTION
High quality irrigation water is becoming increasingly scarce in many areas of the world. Population growth, increased urbanization, and drought conditions can result in a decrease in the quantity of water available for irrigation, while salt water infiltration into fresh water aquifers can affect water quality in coastal areas. Efficient irrigation practices for agricultural production, including greenhouse production, will become increasingly important. Not only is greenhouse irrigation directly affected by the quality of the available irrigation water, greenhouse irrigation practices also can affect water quality. Soilless substrates generally have a low anion exchange capacity, and greenhouse growers typically use water-soluble fertilizers. This combination can result in leaching of water and dissolved nutrients, especially nitrate and phosphate. If this leachate is not collected and recycled, runoff from greenhouses can result in significant non-point source pollution (Lea-Cox et al., 2001). Increasingly strict environmental regulations put pressure on greenhouse growers to irrigate more efficiently in order to conserve water and reduce the risk of negative environmental impacts of their facilities. To improve irrigation practices, a detailed understanding of the spatial and temporal dynamics of the water in the root zone is required.

Many commercial greenhouses use timers to turn irrigation on and off. Timers do not take into account that crop water use changes on a day-to-day basis, based on environmental conditions such as solar radiation, temperature, humidity, and air circulation. For example, daily water use of vinca (Catharanthus roseus) throughout a 40-day period is shown in Figure 1, along with the daily light integral (DLI, total daily

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photosynthetically active radiation). Two trends are clearly evident: 1) water use tends to increase during the production cycle, as a result of increasing plant size, and 2) daily water use fluctuates with changes in DLI (i.e., more light results in increased water use). Although neither of these findings is surprising, such daily fluctuations in water use will result in fluctuations in substrate water content, if irrigation is not adjusted accordingly.

Here we give a brief overview of different soil moisture sensors, describe how such sensors can be used to determine spatial and temporal variability in substrate water content, and discuss how that information can be used to improve the efficiency and uniformity of greenhouse irrigation. Although the emphasis is on the greenhouse production of containerized ornamental plants, similar principles apply to other types of greenhouse production, as well as horticulture in general.

SOIL MOISTURE SENSORS

Substrate water content can be expressed in terms of the energy status of the water in the substrate (water or matric potential) or as the amount of water in the substrate (most commonly expressed on a volumetric basis). Both methods have advantages and disadvantages. Determining the water (or matric) potential of the substrate indicates how easily substrate water is available to plants, but does not provide information on how much water is present or available. Conversely, the volumetric water content of a substrate indicates how much water is present, but not whether this water is available to plants. Using substrate moisture release curves, it is possible to convert matric potential to volumetric water content and vice versa. However, such release curves are substrate specific, and may change over time as the physical properties (especially pore size distribution) of the substrate change. This often occurs as the result of root growth or gradual breakdown of substrate components.

Tensiometers have long been used to measure the matric potential of soilless substrates (e.g., Burger and Paul, 1987). Although tensiometers have proven to be valuable research tools, they can be difficult to use in commercial greenhouses, because of the small size of containers and high porosity of the soilless substrates generally used in greenhouse production. Tensiometers rely on close contact between their porous ceramic tip and the substrate. If the substrate shrinks, or the tensiometer is moved accidentally, this contact may be disrupted and the tensiometer will not function (Zazueta et al., 1994).

In the last 10 years, new soil moisture sensors have become available (e.g., Theta probe and SM200, Delta T, Burwell, UK; ECH2O sensors, Decagon Devices, Pullman, WA, USA). These probes determine the volumetric moisture content by measuring the apparent dielectric constant of the growing medium. This technique is relatively simple and highly reproducible. The Theta probe can be used as a hand-held sensor for measuring substrate moisture content and is ideal for doing spot checks of substrate moisture levels throughout a greenhouse, but can be buried in the soil or substrate for long-term measurements.

ECH2O probes are designed to be installed in soils or substrates for prolonged periods. These sensors can be interfaced with a greenhouse climate computer and used to control irrigation systems automatically, based on user-supplied set points. Dielectric sensors generally require substrate-specific calibrations, because the dielectric properties of different soils and substrates differ, affecting sensor performance.

More recently, hybrids sensors have been developed to use the principle of dielectric sensors to determine the water potential of substrates (e.g., Equitensiometer, Delta T; MPS-1, Decagon Devices). By encasing dielectric sensors in a porous ceramic material, the sensor can determine the water content of the ceramic material. Since the matric potential of the ceramic will equilibrate with that of the surrounding soil or substrate, these sensors can be used to determine the water potential of soils and substrates, based on the moisture release curves of the ceramic material. Such sensors do not require substrate-specific calibrations, because they measure the water content of the ceramic, not that of the surrounding soil or substrate. Unfortunately, such sensors
currently on the market are not very sensitive in the matric potential range where soilless substrates hold most of the plant-available water (0 to -10 kPa, deBoodt and Verdonck, 1972). In addition, it is not clear whether these sensors respond quickly enough to capture the rapid changes that may occur in small containers.

One challenge in sensing the water content or matric potential in soils and substrates is sensor placement. Different sensors measure different volumes of substrate, and it is important to consider the properties of different sensors, when selecting the optimal sensor for a specific task. Tensiometers, and especially micro-tensiometers, measure the matric potential of the substrate in contact with the ceramic tip, and are therefore directly affected by only a small volume of the substrate. Dielectric soil moisture sensors differ greatly in the volume of substrate they measure: smaller probes may be able to sense most of the substrate in small containers, while other sensors may be better suited to larger containers. Understanding the properties of specific soil moisture sensors is therefore critical in interpreting the readings.

LARGE SCALE AND LONG-TERM VARIABILITY IN SUBSTRATE WATER CONTENT

Soil moisture sensors can be used to quantify differences in substrate water content among containers, either by using a handheld meter for spot checks, or by installing soil moisture sensors in containers throughout a greenhouse and periodically measuring them using an automated data collection system. Such measurements can be used to map the spatial heterogeneity of substrate water content within a greenhouse, and these maps can then be used to (re)design the irrigation system to decrease this heterogeneity. Spatial variation in substrate water content can be the result of non-uniformity of the irrigation system, but can also be caused by non-uniformity of environmental conditions within a greenhouse (e.g., de Tourdonnet et al., 2001), which in turn will result in non-uniform water use and growth. Although it has been argued that it is important to increase the application uniformity of greenhouse irrigation systems (Fereres, 1997), the ideal irrigation system does not apply water with perfect uniformity, but instead would apply water based on the spatial distribution of plant water use within a greenhouse.

Soil moisture sensors also can be used to control irrigation. Nemali and van Iersel (2006) described an irrigation system that uses soil moisture sensors (EC-10, Decagon Devices) to control the substrate water content of potted plants at steady, user-selectable levels irrespective of changing environmental conditions or increasing plant size. To reduce issues with temperature and EC sensitivity, the sensors have since been replaced with EC-5 sensors (Decagon Devices), which use a higher measurement frequency. A similar system has since been used to determine the effects of substrate water content on the morphology and growth of *Gaura lindheimeri* (Burnett and van Iersel, 2008), and it was found that control of substrate water content can be used to reduce unwanted stem elongation.

van Iersel et al. (2009) used sensor-based irrigation controllers (Moisture Click, Dynamax, Houston, TX) to automatically irrigate hydrangeas in a commercial greenhouse. This controller uses a single SM200 soil moisture sensor (Delta T) and irrigates when the measured substrate water content dropped below approximately 0.16 m$^3$ m$^{-3}$. Sensor-controlled irrigation was compared to standard, timer-controlled, greenhouse irrigation practices. Substrate water content was measured with EC-5 sensors (Decagon Devices) in containers separate from the container with the SM200 sensor and the volume of irrigation water was monitored with flow meters. Both standard irrigation practices and sensor-controlled irrigation resulted in an average substrate water content of approximately 0.17 m$^3$ m$^{-3}$, but sensor-controlled irrigation (mean substrate water content $\pm SD=0.171\pm0.030$ m$^3$ m$^{-3}$) resulted in less temporal variation than standard irrigation practices (0.167$\pm0.051$ m$^3$ m$^{-3}$, Fig. 2). Although sensor-controlled irrigation resulted in slightly higher substrate water content, and less variation, water use over the 2½ month growing period was reduced by 83% compared to standard irrigation practices. Similarly,
Ristvey et al. (2004) used TDR probes to control irrigation of *Ilex cornuta* in a nursery setting and found that sensor-controlled irrigation reduced water use by 60-85%, with similar reductions in leaching of N and P. Thus, using soil moisture sensors to control irrigation not only reduces temporal variability, but also results in large water savings and reductions in nutrient leaching (Ristvey et al., 2004; van Iersel et al., 2009). A variety of sensors are available that can either be interfaced with automated greenhouse control systems, or that can be used with stand-alone controllers. A good overview of soil moisture sensors can be found at http://www.sowacs.com.

**SMALL SCALE AND SHORT-TERM VARIABILITY IN SUBSTRATE WATER CONTENT**

Soil moisture sensors are a valuable tool for measuring spatial and temporal changes in substrate water content within a single container. For example, Figure 3 shows the substrate water content, measured using EC-5 sensors (Decagon Devices), at four different depths in a 11.3-L container with coleus. This container was subirrigated in the months before data collection, resulting in a root system that was predominantly located in the bottom of the container. At the start of data collection, the container was saturated with water by overhead irrigation, after which the container was not irrigated again. Following saturation, the substrate quickly drained to container capacity. After the initial draining, there was a distinct gradient in substrate water content with much higher water content in the bottom layer (0.65 m$^3$ m$^{-3}$) than in the top layer (<0.40 m$^3$ m$^{-3}$).

During the eight days of this study, the water content in all substrate layers decreased, much faster during the day than at night. Day 3 was particularly overcast, and the substrate water content decreased little during that day (Fig. 3). Perhaps the most surprising finding was that the vertical gradient in substrate water content changed distinctly over time: water content of the bottom layer decreased much more rapidly than that of the upper layers, likely because of the root distribution within the container. Initially this simply decreased the vertical gradient in substrate water content, but from day 6 on, the upper and lower substrate layers had similar water contents, while the two middle substrate layers had the lowest water content. Apparently, the lack of roots in the upper part of the substrate resulted in little water uptake from that substrate layer, and vertical water movement in the container was not fast enough to prevent the middle layers from getting drier than the upper layer.

A more in-depth understanding of water movement can be obtained from looking at the rate of change in substrate water content. Figure 4 shows the rate at which the different layers of the substrate dried out during the fourth day after watering. These data were obtained by fitting sigmoidal curves to the data from day 4 ($R^2$>0.995 for all four depths) and then determining the slope of these curves. The maximum rate of decrease in substrate water content occurred at a depth of 20 cm (bottom of the container), and the pattern at this depth closely followed changes in solar radiation, with a peak around solar noon. This suggests that changes in substrate water content at a 20 cm depth were largely driven by root water uptake from the substrate. Interestingly, the time course of changes in substrate water content were different for the higher substrate layers, with the peak decrease in substrate water content occurring later during the day in higher substrate layers. This suggests that these changes in substrate water content were not primarily driven by root water uptake. Instead, it seems likely that changes in substrate water content in the upper three layers were largely driven by water potential gradients created by water uptake from the bottom substrate layer. As plants took up water from the bottom substrate layer (20 cm), the water potential of this substrate layer dropped, causing water from the 15 cm-deep layer to move down. This in turn would decrease the water potential of the 15 cm-deep layer, causing water from the 10 cm-deep layer to start moving downward, eventually causing water from the top layer to move downward.

Understanding such dynamics of water movement within containers is important in determining the optimal placement of soil moisture sensors for irrigation control: if irrigation control is to be based on plant water use, the soil moisture sensor should be
placed in that part of the substrate where most of the plant water uptake occurs. Since root
distribution can be affected by irrigation method, optimal placement of soil moisture
sensors for irrigation control may depend on how the crop is irrigated. Sensor placement
is especially challenging for crops grown in large containers and for relatively long
periods. For such crops, where root distribution within the container may change
dramatically throughout the production period, it may be necessary to move the soil
moisture sensor as root distribution changes, or it may be possible to use a soil moisture
sensor that can sense the substrate water content throughout most of the container.

CONCLUSIONS

Soil moisture sensors not only can be used to quantify spatial and temporal
variability in substrate water content within a greenhouse, but can also be used to reduce
such variation. Information regarding spatial variability can be used to improve the design
of irrigation systems to better match spatial differences in plant water use throughout the
greenhouse. Changes in daily water use of a crop, caused by changes in environmental
conditions or crop size, can be automatically accounted for by using soil moisture sensors
for irrigation control: when plant water use is high, substrate water content will drop
quickly, and soil moisture sensors can automatically trigger irrigation events in response.
Placement of sensors is important, because of the non-uniform distribution of water
within a container. Thus, care should be taken to assure that the sensors measure water
content in the part of the substrate where most of the water uptake by roots occurs.
Important factors to consider when choosing a particular type or model of sensor are
whether one is more interested in substrate water (or matric) potential or the volumetric
water content of the substrate and the volume of substrate that is sensed.

Although it is clear that soil moisture probes can be useful in quantifying spatial
and temporal variation in substrate water content (both on small and large scales), as well
irrigation control to minimize such variability, the optimal solution for greenhouse
irrigation will likely be a combination of different methods, such as sensors and crop
models (e.g., Bacci et al., 2008).

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Figures

Fig. 1. The daily light integral and daily water use of vinca (Catharanthus roseus). The substrate was maintained at a volumetric water content of 0.47 m$^3$ m$^{-3}$ to ensure that water availability was never limiting. Note that water use tends to increase over time as plants get larger, but is very low on days with a low daily light integral. Light data are missing from day 18 to 28 due to a computer malfunction.
Fig. 2. The substrate water content of hydrangea ‘Mini Penny’ during a 2.5-month period in a commercial greenhouse. Plants were irrigated according to standard nursery practices (control) or with soil moisture sensor-based irrigation controllers. Substrate water content was measured with dielectric probes.

Fig. 3. Changes in substrate water content at four different depths (5, 10, 15, and 20 cm) in an 11.3-L container with coleus (Solenostemon scutellarioides). The container had been subirrigated in the months prior to data collection and was saturated by overhead irrigation at the start of this study, after which the container was not watered again.
Fig. 4. The rate of decrease in substrate water content in four different substrate layers in an 11.3-L container with coleus (*Solenostemon scutellarioides*). Note that the decrease in substrate water content in the bottom layer of the substrate closely follows changes in solar radiation, with a peak at solar noon. Changes in substrate water content are smaller, and peaks occur later in the day in higher substrate layers.