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Characterizing Air and Water Content of Soilless Substrates to Optimize Root Growth

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The physical properties of soilless substrates should be well characterized, since it is well-known that it is the ratio of air:water that most influences root growth, and overall plant growth in container production. However, other factors such as container height, geometry, and substrate handling can also have a profound effect on these variables. We tested the performance of Ech$_2$O capacitance sensors and their ability to accurately monitor water content in a range of soilless substrates with differing physical properties. Desorption curves were generated for each substrate with simultaneous readings, using 5-cm and 20-cm sensors and a custom-built desorption table. The precision of these sensors was confirmed with all soilless substrates tested, although the results revealed that a surprising amount of the total water in these substrates was beyond the commonly accepted range of readily-available water for plants in containers. We are now confident that we can use these sensors, to more precisely schedule irrigation water applications, using the desorption curves from the data we derived in these studies.

INTRODUCTION

Optimal plant growth is dependent on providing a balance of air and available water in the root zone, to maximize root growth and reduce the prevalence of disease (Argo, 1998). Fonteno et al. (1995) stated that the four major factors which affect air and water dynamics in soilless substrates include not only substrate components (ratios) and watering practices, but also the height and shape of the container and the substrate handling procedures (i.e., modifying substrate packing and bulk density). Typically, soilless substrates are composed of one or more materials to ensure adequate aeration and drainage, since organic particles tend to break down over time. Inorganic components, such as perlite and polystyrene, add volume to these mixes and help reduce poor aeration.

Of these factors, container height is important, as it affects not only the total air space in the substrate (as influenced by gravitational forces) but it also affects the total volume, and hence the total water available to plant roots. Changes in air : water are exacerbated in small containers, as illustrated by Fonteno et al. (1995), who showed a 3–4 times increase in air space in a number of substrates, merely by increasing plug height from 2.5 cm (1 in.) to 5 cm (2 in.).

The objective of this research was to test the performance of soil moisture capacitance sensors (Ech$_2$0 series; Decagon Devices, Pullman, Washington) and their ability to accurately monitor water content in a range of soilless substrates. By understanding the physical properties of various substrates and ensuring that we can precisely measure the water content *in situ*, we will have the confidence to integrate these sensors into wireless networks for real-time irrigation management.

MATERIALS AND METHODS

The physical properties of five soilless substrates were characterized, to determine differences in container capacity and gather information on the percent air and readily available water. The substrates tested included perlite (horticultural grade A-20, Pennsylvania Perlite Corp., Bethlehem, Pennsylvania), two commercial nursery substrates, pine bark and sphagnum peat moss mix (4 : 1, v/v), and 100% pine bark, Sunshine Professional LC1 [sphagnum peat moss and perlite (4 : 1, v/v)], and 100% Sri Lankan coir (coconut fiber) substrate. These substrates were chosen on the basis of their use in the container nursery and greenhouse industry and/or their differing ability to hold and release water. We also wanted to compare our results to previous methods and results [Bunt, 1961; De Boodt and Verdonck, 1972; Karlovich and Fonteno, 1986; Drzal et al., 1999], since one of the major objectives of this study was to accurately calibrate Ech$_2$O capacitance sensors for use in these soilless substrates. Desorption curves were generated for each substrate with simultaneous readings using 5-cm and Ech$_2$O capacitance probes, a custom-built desorption table, and positive (compressed air) pressure (Fig. 1). Ten replicate columns, 5.7 cm (2.2 in.) tall and 12.7 cm (5.0 in.) in diameter, were simultaneously desorbed for each substrate with three successive runs (n = 30). The full methodology for the 20-cm columns was outlined by Arguedas et al. (2007). All substrates in columns were uniformly packed by incrementally filling about 1/3 of the column with

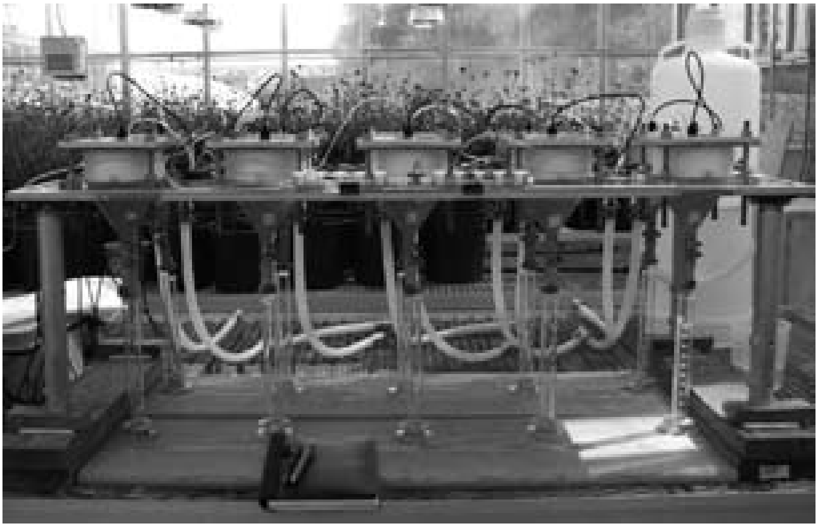

Figure 1. Photograph of the desorption table experimental setup used to calibrate the 5-cm Decagon Ech$_2$O sensors in 5.7 cm height and 12.7 cm diameter PVC columns (n = 10).

substrate, saturating and draining the water, and repeating this procedure, to ensure that a natural distribution of particles occurred when the column was packed. When fully packed, a polycarbonate lid with an embedded and sealed sensor was positioned centrally and carefully placed vertically into the substrate. The plate and sensor were then bolted down onto each column, to give a pressure-tight seal. The columns were then slowly re-wetted from the base, to gradually force all air out and to allow for a uniform absorption of water by all particles. The substrates in the columns were allowed to fully saturate and establish equilibrium for at least 6 h. Upon saturation, columns were allowed to drain freely overnight by gravity (0 kPa), thus reaching container capacity. The volume of water expressed overnight was collected and measured for each column, providing the data for air space. The following day, positive gas pressure was applied and monitored with a digital pressure gauge (GE Druck DPI 104) and adjusted by a gas pressure regulator (E12 244D) at the following pressure increments: 1, 2, 4, 6, 8, 10, 15, 20 and if necessary at 40, 60, 80, and 100 kPa. Using a standardized method, we collected the volumes expressed from the columns at each pressure, with readings being taken every 10 min throughout the run. When five or more of the columns did not change in volume by more than 1 ml, the subsequent pressure increment was applied. Runs generally took between 6 and 18 h, depending upon the substrate and column height tested. The volume of water leached at each pressure increment was totaled for each replicate column. The capacitance sensor data were continuously measured (every 10 sec) during each run, using a Campbell Scientific CR23X micrologger and a modified datalogger program (pers. commun., Colin Campbell, Decagon Devices). Upon completion of the desorption run the final total desorbed water was recorded (VW), the substrate in each column was carefully removed, weighed (WW), dried at 60 °C for 96 h, and re-weighed to determine dry weight (DW). Container capacity (CC) or the water contained in the substrate after saturation and drainage was calculated as: CC = [(WW-DW) + VW].

RESULTS AND DISCUSSION

The physical properties for all five substrates tested in the 5-cm columns are given in Table 1.

The perlite and coir substrates had the lowest container capacities (≈345 ml) compared to the substrates containing peat (≈525 ml). This resulted in very similar total porosity (TP) and air-space (AS) content for these substrates, although the coir substrate had a significantly higher TP and AS than the other substrates. This may be due to the proportions of coir fiber and copit (the spongy material between the fibers in the husk) in this substrate (not measured). However, the proportions of readily-available water (RAW; 0–10 kPa) were significantly higher in the two substrates containing peat (47% and 57%) compared to the other three substrates (ranging from 35% to 37%). This resulted in a higher proportion of progressively unavailable water (PUW >10 kPa) in the substrate.

The regression curves for the sensor output vs. volumetric water content were very highly significant, showing that both the Ech$_2$O 5-cm (Figs. 2A; 3A) and Ech$_2$O 20-cm (Figs. 2B; 3B) sensors were able to precisely measure the available water at very low pressures (water tensions) in these substrates. This is extremely important, since it can be seen that the proportion of water readily available to the plant at these very low water tensions (0–10 kPa) is well characterized by the

Table 1. Mean (n = 10) bulk density (BD), container capacity (CC), total porosity (TP), air space (AS), and mean (n = 30) easily available water (EAW), water buffering capacity (WBC), and progressively unavailable water (PUW) of five commercial soilless substrates in 5-cm high columns.

		Perlite	Pine bark and peat (4 : 1, v/v)	Coir	Pine bark	Peat and perlite (4 : 1, v/v)
BD	(g•cm^{-3})	0.108	0.193	0.069	0.194	0.087
CC[†]	(ml)	349	517	341	419	534
TP	(%)	62.8	73.6	84.0	67.8	76.4
AS	(%)	15.6	2.0	37.0	9.7	2.4
	Pressure (kPa)			Distribution of water (%)		
EAW	(1 to 5)	36.0	40.0	32.6	34.6	43.7
WBC	(5 to 10)	1.2	7.0	2.1	2.2	13.1
PUW	(>10)	62.8	53.0	65.3	63.2	34.1*

[†] Total volume of the 5-cm column = 722 ml. Note that CC = TP - AS. Use CC values to interconvert data.

* An additional 9.1 % water was expressed from this substrate between 10 and 60 kPa (to total 100%).

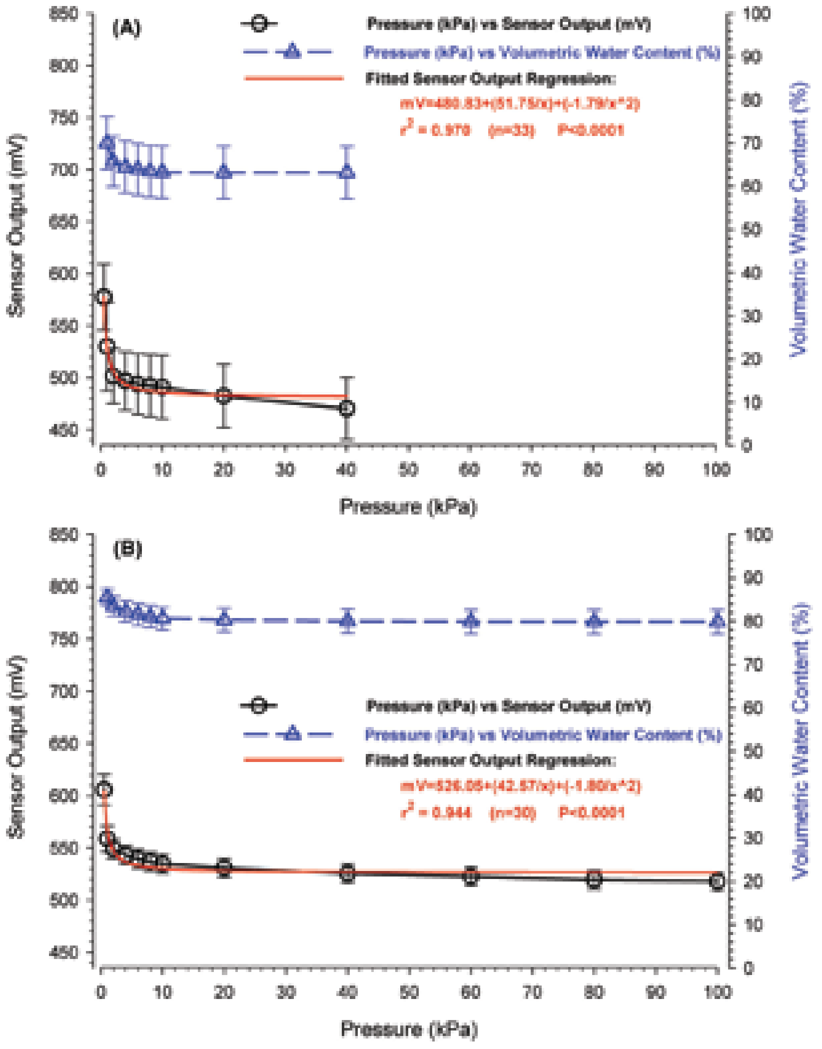

Figure 2. Simultaneous sensor output (mV) and volumetric water content (%) vs. air pressure applied (kPa) for Ech$_2$0 5-cm sensors (Fig. 2A) and Ech$_2$0 20-cm sensors (Fig. 2B) in a 100% perlite substrate.

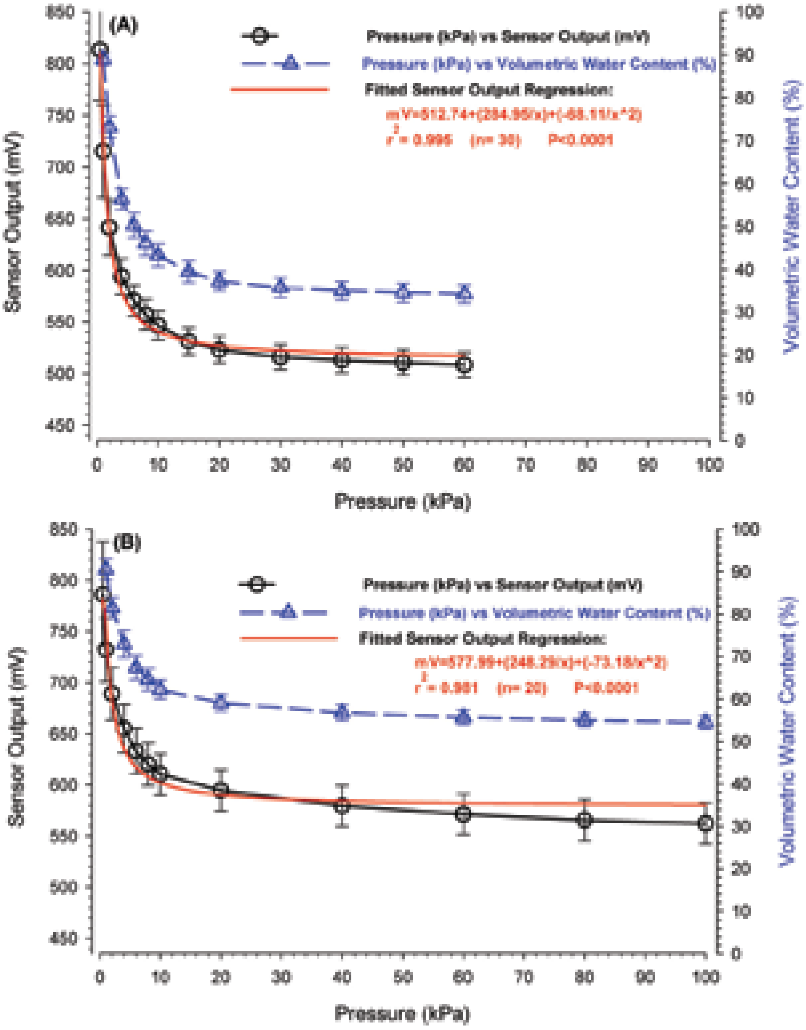

Figure 3. Simultaneous sensor output (mV) and volumetric water content (%) vs. air pressure applied (kPa) for Ech$_2$0 5-cm sensors (Fig. 3A) and Ech$_2$0 20-cm sensors (Fig. 3B) in a peat and perlite (80 : 20, v/v) (Sunshine LC1) commercial substrate.

response (Figs. 2 and 3) of both sensors. The percentage of water extracted from each substrate from 10–100 kPa was negligible, except for the peat : perlite mix (see footnote, Table 1). The percentage of progressively unavailable water (PUW) was surprisingly high in all the substrates and combinations tested (Table 1; Figs. 2 and 3). For perlite, this proportion equaled 63% and 79% in the 5-cm and a 20-cm column, respectively (volumetric water content axis intercepts, Fig. 2A and Fig. 2B). We acknowledge that a large proportion of this water (> 10 kPa) may, in fact, be available for uptake by roots, but Keihl et al. (1995) showed that the growth of chrysanthemum [*Dendranthema grandiflorum* (Ramat.) 'Kitamura'] in soilless substrates was reduced at water tensions as low as 16 kPa. For this reason, we consider that the set-points for scheduling irrigations using these sensors should ideally be from 1–10 kPa in most substrates. This should of course be confirmed by empirical methods, once the sensors are in place in the root zone.

Since container height and substrate water retention properties have a complex effect on the proportion of air and water, we should be careful not to over irrigate materials with high percentages of peat moss, since the air space in these substrates tends to be very low. In contrast, substrates with a larger particle sizes and higher air fractions are easily underwatered, since the fraction of readily available water is very low, particularly in small-volume containers. By using these capacitance sensors, we are confident that we can very precisely manage water applications, as long as those sensors are calibrated to that particular substrate, and placed in an appropriate location. Our group (Lea-Cox et al., 2007) is working towards deploying sophisticated, low-cost wireless networks in commercial operations that will have the ability to attach various types of sensors, including air and soil temperature, relative humidity, leaf wetness, light (photosynthetically active radiation), and water and electrical conductivity sensors, among others. Our goal is to have the ability to measure environmental data with sensor nodes that are robust (weather-proof), lightweight, and portable, that can be moved anywhere in the operation to monitor "trouble-spots," and eventually assist in irrigation scheduling and other management decisions. Providing a suite of environmental data via the internet to the desktop of a grower is nearing reality and this capability will enable us to manage our resources more efficiently and increase the profitability of our operations in the future.

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