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Research Paper

A novel dielectric tensiometer enabling precision PID-based irrigation control of polytunnel-grown strawberries in coir

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The benefits of closed-loop irrigation control have been demonstrated in grower trials which show the potential for improved crop yields and resource usage. Managing water use, by controlling irrigation in response to soil or substrate moisture changes, to meet crop water demands is a popular approach but requires substrate specific moisture sensor calibrations and knowledge of the moisture levels that result in water deficit or over-watering. The use of water tension sensors removes the need for substrate specific calibration and enables a more direct relationship with hydraulic conductivity. In this paper, we present a novel dielectric tensiometer that has been designed specifically for use in soil-free substrates such as coir, peat and Rockwool with a water tension measurement range of −0.7 kPa to −2.5 kPa. This new sensor design has also been integrated with a precision PID-based (drip) irrigation controller in a small-scale coir substrate strawberry growing trial: 32 strawberry plants in 4 coir growbags under a polytunnel. The data illustrates that excellent regulation of water tension in coir can be achieved which delivers robust and precise irrigation control - matching water delivery to the demands of the plants. During a 30-day growing period vapour pressure deficit (VPD) and daily water use data was collected and the irrigation controller set to maintain coir water tension at the following levels: −0.90 kPa, −0.95 kPa and −1 kPa for at least 7 consecutive days at each level. For each set-point the coir water tension was maintained by the irrigation controller to within ±0.05 kPa. Meanwhile the polytunnel VPD varied diurnally from 0 to a maximum of 5 kPa over the trial period. Furthermore, the combination of the dielectric tensiometer and the method of PID-based irrigation control resulted in a linear relationship between daily average VPD and daily water use over 10 days during the cropping period.

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1. Introduction

Sensors that use the dielectric properties of moist soil to measure soil water content are now widely available and, in many cases, have replaced the neutron probe as the instrument of first choice. This is largely due to safety considerations and the ease of logging offered by modern dielectric sensors. The most effective approaches to soil management, however, require measurement of the matric potential of soil water. Advances in technology to measure matric potential have been modest compared with those for soil water content.

Matric potential can be measured directly in a water reservoir that is connected hydraulically to the soil by a porous filter. In order to yield reliable results, both reservoir and porous filter must remain saturated throughout the period of measurement. To this end, devices that employ this technique (water-filled tensiometers) are typically fitted with ceramic filters with small air entry potentials in order to prevent desaturation when subjected to negative potentials. However, conventional water-filled tensiometers typically only work over the limited range of 0 to −85 kPa and require regular maintenance if long-term measurements are required (Whalley et al., 2009). Recent research into saturation techniques and tensiometer design has led to the development of a new class of high capacity tensiometer in which the magnitude of measurable suction is limited only to the air entry potential of the porous ceramic filter and the tensile strength of water (e.g. Take & Bolton, 2003). Although these devices can work successfully down to matric potentials as small as −2 MPa, their widespread use has been limited by the present lack of a commercially-available device and by the technical experience needed for the saturation and measurement processes.

The limited range of conventional water-filled tensiometers has led to the development of a second strategy for the measurement of matric potential, the porous-matrix sensor (e.g. Or & Wraith, 1999; Whalley et al., 2001). In contrast to the direct measurement of matric potential, the porous ceramic is chosen so that it will readily alter its degree of saturation to maintain equilibrium with the soil water. If the water retention characteristic of the porous matrix is known, measurement of the water content of the ceramic will allow the matric potential of the soil water to be estimated indirectly. Originally, these sensors used plaster of Paris as the porous matrix and electrical resistance measurements of matrix were calibrated against matric potential (Bourget, Elrick, & Tanner, 1958). Such sensors are now commercially-available and are best suited to dry soils (matric potential < −500 kPa), where they work well because hysteresis in the sensor is small at these matric potentials. Recently, they have been modified by increasing the pore size of the porous matrix, to obtain a sensor that will work at matric potentials between 0 and −200 kPa. However, there is a requirement, especially in horticulture to measure very high matric potentials (0 to −10 kPa), especially when controlling irrigation in horticultural substrates.

Closed-loop irrigation control employing soil moisture sensors has been demonstrated in grower trials which show the potential for improved crop yields and resource usage. Managing water use by controlling irrigation in response to changes in soil moisture conditions to meet crop water demands is a popular approach but requires knowledge of closed-loop control practice, substrate specific sensor calibrations and the water status limits that result in water-deficit or excessive run-off.

A key benefit of employing water tension (matric potential) measurements instead of soil moisture measurements is that a substrate specific sensor calibration is not required. However, whilst sensor based irrigation control has been performed in soil with soil moisture and tensiometer based measurements (Muñoz-Carpena, Bryan, Klassen, & Dukes, 2003; Whalley et al., 2009) the lack of suitable water tension sensors has made similar studies in soil-free substrates difficult. Furthermore, in the literature (Michel, 2010; Raviv, Lieth, Burger, & Wallach, 2001) such a sensor may have useful application in a wide range of soil-free substrates whilst also providing better management of hydraulic conductivity, a substrate property that can decrease sharply with water content (Raviv et al., 2001).

In this paper, we present a robust dielectric tensiometer designed for use in soil-free substrates where: the optimal substrate water tension that avoids plant water-deficit and over-watering conditions may be in the range of −0.7 kPa to −2.5 kPa and does not require the degassed water filling process of a water-filled tensiometer. In this respect, our paper describes a novel development because previous accounts of dielectric tensiometers have been concerned with dry soil at low matric potentials (e.g. Whalley et al., 2009). To calibrate sensors at very high matric potentials (e.g. −0.7 kPa to −2.5 kPa) we used a manometer based calibration. The application of the dielectric tensiometer described in this work is concerned with the control of irrigation in strawberry production. Matric potential data from the dielectric tensiometer was used in a PID irrigation controller (Goodchild, Kühn, Jenkins, Burek, & Dutton, 2015). This PID irrigation control system was evaluated in a small-scale growing trial using a coir substrate and has demonstrated that water tension can be maintained by precisely regulating the water flow under varying vapour pressure deficit (VPD) conditions. The context of this work is the need to reduce water use. Our paper describes a novel sensor optimised to control water status of coir, or similar growth substrates, in near-saturated conditions. The exemplar application in strawberry production illustrates that developments we describe may help industry reduce water consumption.

2. Materials and methods

2.1. *Description of the dielectric tensiometer*

The operation of a dielectric tensiometer takes advantage of the relatively high dielectric constant of water with respect to that of a porous substrate. The change in dielectric constant between a dry porous material and a water saturated porous material can be measured with appropriate electronics circuitry. This dielectric tensiometer is based on patented soil moisture measurement technology (Lock, 2011).

A characterised porous material is employed in the sensor to provide a means of achieving a known conversion from moisture content to substrate water tension in the sensor's porous material which can be measured by the electronics. The hydraulic connection between the sensor's porous material and substrate provides a fluid path that equilibrates the water tension (capillary forces) in the sensor's porous material with that in the substrate.

The dielectric tensiometer presented in this work is shown schematically in Fig. 1 and consists of: the moisture content sensing electronics, a high-porosity open cell micro-lattice structure which is a polyurethane based hydrophilic reticulated and compressed foam supplied by FaraPack Polymers Ltd., Sheffield, UK., and a stainless-steel cage (Goodchild, Jenkins, & Saywell, 2016). This cage performs two tasks. Firstly, it is a means of securing the hydrophilic foams to the body of the sensing electronics. Secondly, the cage provides a screen to retain the electric field within the foam thereby avoiding errors resulting from detecting water in the surrounding substrate.

2.2. *Precision irrigation control using a modified proportional, integral and derivative control algorithm*

The proportional, integral and derivative (PID) controller has been applied to many applications where precise control is required. A popular application area is temperature control where many commercial products are available (OMEGA Engineering, INC., www.omega.com). The application of the PID controller for irrigation is shown in Fig. 2 where the classic PID controller (Schwarzenbach & Gill, 1984, pp. 224–234) consists of a signal comparator which compares a measured feedback signal to a (user defined) set-point, the difference between these is the error signal. This error signal is then processed using weighted proportional, integral and derivative functions and the output from each function is summed to create a control signal that is used to drive an actuator. These weightings can be derived theoretically, which is often difficult to achieve, and by using empirical methods (Goodchild et al., 2015; Ziegler & Nichols, 1942). In this study, the actuator is a solenoid valve and the PID controller is used here to estimate, or prescribe, the volume of water required for each irrigation event in order to maintain constant substrate water conditions.

The classic PID controller has a number of benefits, including: precision control, stability and the ability to respond quickly to changing loads or user set-point (Schwarzenbach & Gill, 1984, pp. 224–234). However, one problem associated with the PID controller which may have limited its adoption in irrigation systems is controller wind-up. In the literature, in the case of a significant rainfall event there is a risk the PID controller can go into a windup condition (Romero, 2011; Romero, Muriel, Garcia, & Muñoz de la Peña, 2012) which may result in a loss of control and a significant delay before control is resumed. For example, in a PID system that is under control, i.e. the parameter under control is at the user's set-point and in steady-state, one would expect the PID signal processing of the error signal to deliver proportional and derivative function outputs that are close to zero. However, the PID output that drives the actuator at a level to maintain steady state control is largely derived from the output of the integral function, a level that has been determined over an extended period of time. External events which cause the proportional and derivative functions to provide rapidly changing outputs may result in a relatively small change to the output of the integral function. In the case of a rainfall event resulting in the soil moisture being above a desired set-point over an extended period of time, this will initially cause the integral function to reduce the steady state control level. If left unconstrained the integral function could reach a level that is equivalent to negative water application volume which will continue to increase, or windup, over time (Romero, 2011; Romero et al., 2012). In this situation, once the plant's water demand has increased to a point that the soil moisture reaches a level below the desired set-point, the

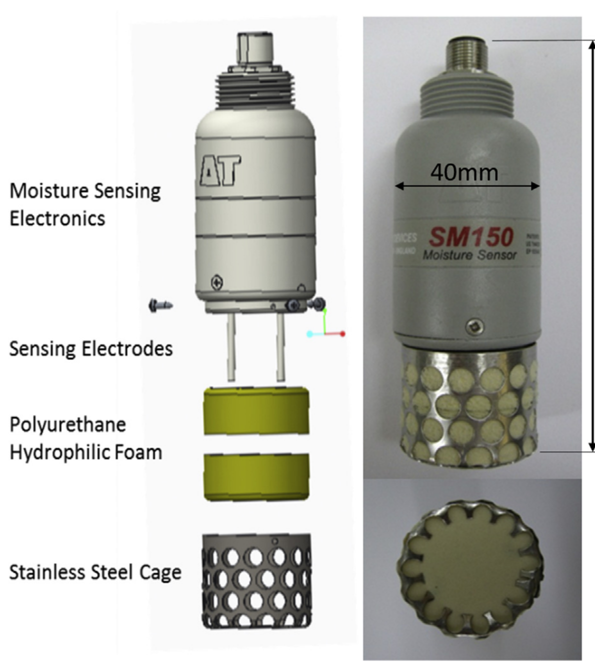

Fig. 1 – A prototype dielectric tensiometer is shown schematically alongside a completed device (based on an SM150 soil moisture sensor) as used in this study. The dielectric tensiometer has two foams, each foam is 36 mm in overall diameter and 15 mm thick. The dimensions of the dielectric tensiometer are, length 119 mm and 40 mm in overall diameter.

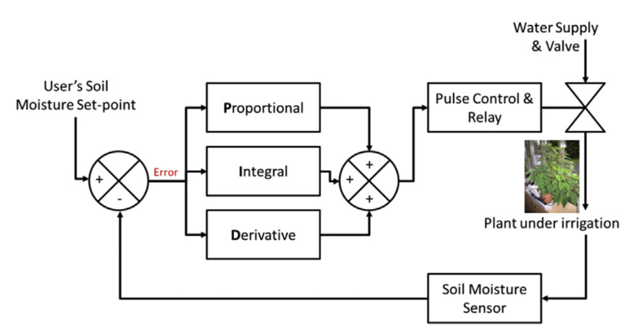

Fig. 2 – The block diagram of a PID controller based irrigation system using soil moisture sensor feedback as described in Goodchild et al. 2015, where the integral is constrained to avoid wind-up conditions.

integral function is still in a windup condition. This could offset the output from the proportional and derivative functions, causing under watering events until the integral function recovers from the windup condition, this assuming the soil moisture level remains below the set-point. More recently this problem has been addressed in a soil moisture based PID irrigation controller by applying constraints to the integral function which eliminates wind-up in a classic PID controller and thus avoids potential for periods of over or under watering (Goodchild et al., 2015). In this work, the integral function has been constrained to values equivalent to positive water application volumes (within the range of 0 to a maximum of half the peak daily water requirement), whilst allowing the proportional function to operate as it would in a classic PID controller. A further simplification of the classic PID controller has been to set the derivative function scaling factor to zero, typically the derivative function is employed to manage closed-loop instability.

The ability of a constrained integral PID-based controller employing a dielectric tensiometer to maintain precise control of substrate water tension and deliver appropriate daily irrigation volumes whilst responding appropriately to diurnal VPD cycles will be assessed in this experimental work.

2.3. *Experimental growing trial arrangement*

To evaluate the performance of the dielectric tensiometer and a PID-based irrigation controller, a small-scale system consisting of 32 strawberry (*Fragaria* × *ananassa*) plants in 4 bags of Botanicoir coir (www.botanicoir.com) were installed in a single row of a Haygrove Ltd (www.haygrove.com). double row substrate system under a polytunnel (at Delta-T Devices Ltd., Burwell, UK, latitude 53°18′ N, longitude 0°02′ E).

Drip irrigation was installed with 4 drippers per bag, a solenoid valve was used with a flow-meter to monitor irrigation water volume. The PID control algorithm was implemented in a GP2 Data Logger and Controller (Delta-T Devices Ltd.) as outlined in the literature (Goodchild et al., 2015) but with substrate water tension feedback provided by the dielectric tensiometer described above. A flow meter (resolution: 1 L) recorded the delivery of PID derived irrigation volumes, the irrigation interval was set to 30 min. The sensor recording period was set to 2.5 min.

Solar radiation data (W m^{-2}) was collected from a BF5 Sunshine Sensor (Delta-T Devices Ltd.) and vapour pressure deficit (kPa) was calculated in the GP2 Data Logger and Controller (Allen, Pereira, Raes, & Smith, 1998; Murray, 1967) using relative humidity (from an RHT4 sensor, Delta-T Devices Ltd.) and air temperature measurements, the latter via the GP2's internal temperature sensor. These environmental measurements we recorded every 2.5 min.

3. Results and discussion

3.1. *Calibration of the dielectric tensiometer*

The calibration of the dielectric tensiometer was performed using a simple manometer arrangement where the liquid interface to the foam was achieved using a porous ceramic pressed against the lower foam, as shown in Fig. 1. Silicon rubber was wrapped around the stainless-steel cage to minimise evaporative water losses and reduce equilibration times, measurements were taken at 20 °C ± 0.1 °C. The drying response of the dielectric tensiometer is shown in Fig. 3 with a van Genuchten model (van Genuchten, 1980) fitted to the sensor's voltage output in millivolts (mV).

The van Genuchten model for water retention in soil is given as:

$$\theta = (\theta_s - \theta_r)\left[1 + (\alpha h)^n\right]^{-m} + \theta_r \quad (1)$$

where:

- θ is water content at water potential h,
- θ_s and θ_r are saturated and residual water contents of the porous material respectively,
- α, n and m are empirical coefficients, where: $m = 1 - 1/n$

In Fig. 3, the van Genuchten model has been applied to the voltage output of the dielectric tensiometer where: θ, θ_s and θ_r are replaced with mV voltage levels, as shown in Table 1. The fitted curve was then used to generate a look-up table for the GP2 Data Logger and Controller so that water tension measurements could be logged using interpolated mV voltage readings. The resulting water tension data set is shown in Fig. 4.

We tested a number of porous materials for their suitability for use in our dielectric tensiometer. We selected a porous foam which has a similar water release characteristic to the growth substrates commonly used in horticulture. In a comparison of the hydraulic properties of different greenhouse-substrates Fields, Fonteno, Jackson, Heitman,

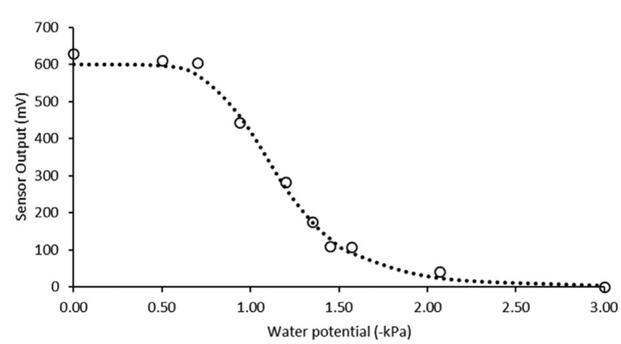

Fig. 3 – The manometer derived drying response for the SM150 based dielectric tensiometer with a fitted curve using the van Genuchten model, shown by the broken line.

Table 1 – The van Genuchten parameters used for the modelled fit shown in Fig. 3.

van Genuchten Parameters	
θ_s (Saturated foam)	629 mV
θ_r (Dry foam)	0.0 mV
α	0.905 kPa^{-1}
n	6.081
m	0.836

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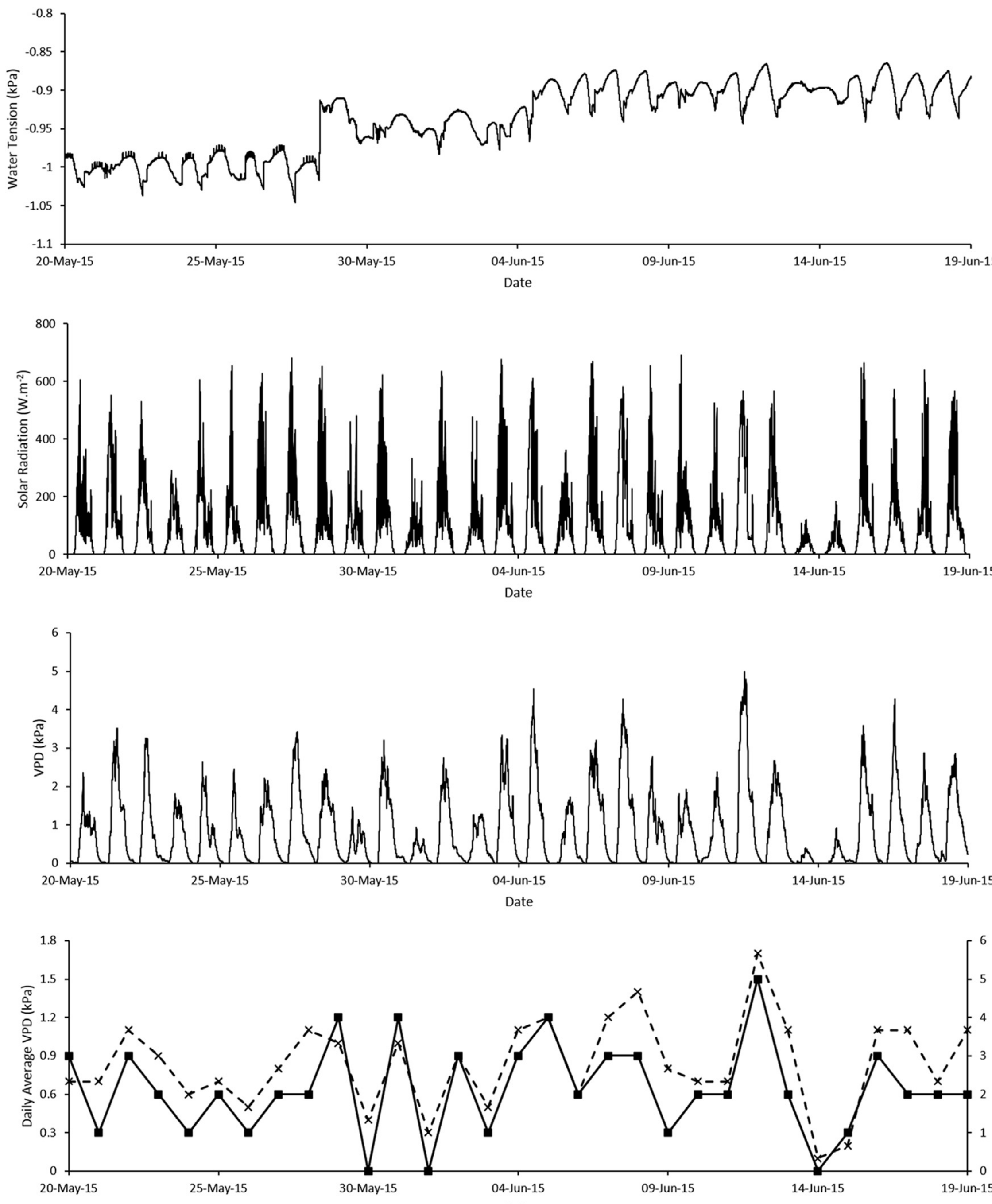

Fig. 4 – Data collected during the 30-day growing trial up to and including 10 d of cropping. Water tension regulation at −1 kPa, −0.95 kPa and −0.9 kPa has been achieved with the dielectric tensiometer and PID-based irrigation controller for a wide range of solar and VPD conditions. Daily water use is shown by the solid line and the '■' symbols, average daily VPD is shown by the broken line and the '×' symbols.

and Owen (2014) showed that typically they drained to a residual water content during drainage from saturation at matric potential as between −1 and −10 kPa. The porous foam used in our sensor was highly sensitive to drainage between −0.5 and −3 kPa, which makes it suitable for use in the measurement of matric potential in growth substrates. An important point to note is that while there may be considerable hysteresis in the drying and wetting curves on both the greenhouse-substrates and the foam used in our sensor, this is of little practical importance. From an initial state of saturation, the greenhouse-substrates, and the foam in our sensor, will dry slowly, but will wet rapidly on irrigation. Thus, for the vast majority of time our sensor will be on the drying curve shown in Fig. 3.

Strawberry growing trial data – irrigation control & dielectric tensiometer evaluation

During a 30-day growing period leading up to and including 10 d of the cropping period, vapour pressure deficit (VPD) and daily water use data was collected. The irrigation controller was set to maintain coir water tension at the following levels: −0.90 kPa, −0.95 kPa and −1 kPa for at least 7 consecutive days at each level. These water tensions were chosen to avoid run-off and plant water deficit (Else, 2013) in addition to testing the capabilities of the dielectric tensiometer and the PID irrigation controller.

In Fig. 4, water tension data is presented where the PID irrigation controller has been set to maintain the water tension at −1 kPa, −0.95 kPa and −0.9 kPa for a wide range of solar and VPD conditions. The level of precision of water tension control can be seen in Fig. 5 against VPD and at each set-point the variance in coir is less than ±0.05 kPa. This result would appear to support the use of the new dielectric tensiometer and precision irrigation control algorithms such as PID. Furthermore, by achieving this level of substrate water tension stability the daily water use data, shown in Fig. 4, is clearly responding to the environmental driver of VPD (despite the low-resolution of the irrigation volume measurements). The relationship between daily water use and daily average VPD is presented in Fig. 6 for the 10 d during cropping. This region was chosen because it was the largest sample period without any change to the set points. Furthermore, this data includes the widest range of daily average VPD values.

The data and results presented in Fig. 5 illustrates precision irrigation control using a novel dielectric tensiometer and the constrained integral PID control algorithm. This precision irrigation controller has managed irrigation events to provide water tension stability in coir to better than ±0.05 kPa. Such levels of control could better manage hydraulic conductivity variance in soil-free substrates. Furthermore, from the inspection of the coir tension data shown in Fig. 4 and substrate temperature (not presented) it appears that a source of variance in water tension measurement results from the negative temperature dependence of the dielectric constant of water. The authors believe that this artefact in the measurement method can be resolved with a substrate temperature correction to further improve the level of control (Goodchild, Kühn, Nicholl, & Jenkins, 2016).

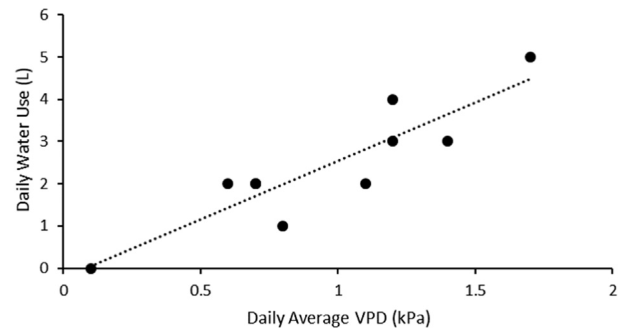

Fig. 6 – The relationship between daily water use and daily average VPD over 10 days during the cropping period 5th–14th June 2015. Daily water use recorded with 1 L resolution. The linear trendline equation is, $y = 2.7822x - 0.243$, where, $R^2 = 0.8014$.

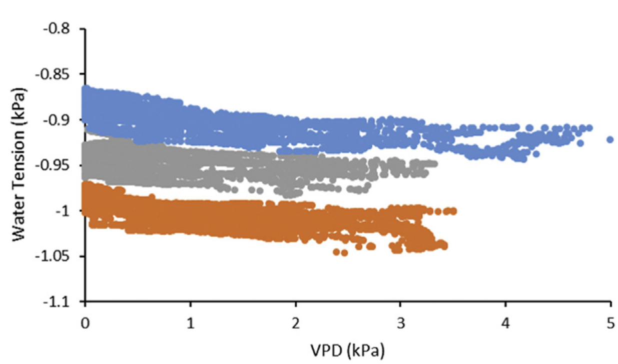

Fig. 5 – PID irrigation control of coir water tension for set-points of −1 kPa (orange circles, from 16th to 27th May), −0.95 kPa (grey circles, from 28th May to 3rd June) and −0.9 kPa (blue circles from 5th to 14th June) under a wide range of VPD conditions – from the data shown in Fig. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Conclusions

In this paper, we describe the development of a novel dielectric tensiometer for use in high porosity soil-free substrates, such as coir, peat and Rockwool, which has:

- a water tension measurement range of −0.7 kPa to −2.5 kPa which can be calibrated and characterised using the van Genutchen water release equation,
- been successfully integrated with a precision closed-loop irrigation controller to deliver excellent regulation and stability of water tension in coir to within ±0.05 kPa.

Data collected from a small-scale strawberry growing trial employing the dielectric tensiometer and a constrained integral PID-based precision irrigation controller has illustrated that:

- the constrained integral PID controller is able to respond to changes in environmental conditions and the diurnal cycle whilst delivering prescriptive irrigations and precise irrigation control,
- precise regulation of water tension in coir (±0.05 kPa) is possible over a wide range of VPD loads and solar radiation levels.

We conclude that this new dielectric tensiometer addresses the need for a sensor that can deliver accurate measurement of water tension in soil-free substrates, such as coir, and is suitable for precise control of substrate water status in closed-loop irrigation control systems. To study this environment (i.e. coir) we have developed a sensor that can be used to measure small changes in matric potential in a near-saturated environment. This meets a requirement that hitherto has not been met by any commercial sensor. Thus, our contribution in this respect is novel. Our exemplar application, concerned with the irrigation of strawberry crops, involved the use a PID control approach implemented in a commercially available logger which has been described elsewhere. However, within irrigation control PID is not routine and our data presented in this paper give a clear account of its merits. We could maintain a near constant moisture environment in the coir despite large changes in vapour pressure deficit and in turn water use. We believe that this control method has the potential to save water use in irrigation and our data in this paper should be seen as a generic example of what is possible.

Disclosure statement

Dr. Martin Goodchild and Malcolm Jenkins are employed by Delta-T Devices Ltd., who develop and sell tensiometer and other equipment. All authors have been fully involved in all aspects of the study and the paper.

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