Plant water use and drought stress physiology: Manipulating irrigation for efficient water use and high quality plants

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Abstract

Irrigation systems that can control watering based on soil moisture sensors are a powerful tool for both greenhouse irrigation and drought stress physiology research. This paper provides an overview of research at the University of Georgia. Three studies are discussed: a study describing the effects of substrate water content (θ) on growth and water use of petunia, a study looking at growth and drought stress physiology of vinca, and a study looking at control of both irrigation and fertigation using *in situ* soil moisture and electrical conductivity sensors. This research has practical applications for greenhouse irrigation and fertilization management, while also furthering drought stress physiological research.

Introduction

Managing global water resources is one of the most pressing challenges of the 21st century. Population growth and increased urbanization have increased competition for water by agricultural, industrial and domestic users. Agricultural water use in many areas of the world is not sustainable (Jury and Vaux, 2005). To meet the long-term needs of the world's population, it is crucial that the efficiency of agricultural water use is increased (Howell, 2001) and science and technology must play an important role in addressing problems arising from a global water shortage.

The greenhouse industry is not immune from these issues, and improving irrigation efficiency must play an important role in making greenhouse production more sustainable. Various US states have legislation regulating agricultural water use and quality. Some legislation requires greenhouses and nurseries to develop nutrient management plans describing efforts to reduce non-point source pollution (Lea-Cox and Ross, 2001). Sustainable greenhouse irrigation practices are not just important for the US but also in many other greenhouse production areas.

Good irrigation management is an important best management practice in ornamental crop production, reducing runoff of nutrient- and pesticide-rich water from production sites (Tyler et al., 1996; Briggs et al., 1998, Lea-Cox and Ross, 2001). Better control of irrigation can have other benefits as well: better plant quality, more compact plants (Burnett and van Iersel, 2008) and reduced damage from root pathogens (Powell and Lindquist, 1997). In addition, more efficient irrigation can have direct economic benefits, since less electricity or fuel is needed to pump the irrigation water.

A promising approach for improving irrigation practices is the use of real-time sensing technology to detect the water status of the soil or substrate and to use those

measurements to control irrigation. This approach is readily applied and allows for easy automation (Jones, 2004). Jones (2007) concluded that soil water content is the most valuable measure of plant or soil water status for purposes of irrigation scheduling.

We have developed an automated irrigation system that measures θ in multiple containers, and irrigates them based on container-specific θ thresholds. This irrigation system can maintain θ within a narrow range and automatically adjusts irrigation as plants get larger or environmental conditions change (Nemali and van Iersel, 2006). We have since modified this irrigation system to allow for precise determination of the daily amount of water applied to each container. This irrigation system allows for maintenance of different substrate water content (θ) levels, and thus makes it possible to evaluate whole plant physiological and morphological response to drought stress.

An even more recent development is the availability of sensors that can measure both θ as well as the bulk electrical conductivity (EC) of the substrate. Since EC can be used as an indicator of nutrient availability in the substrate, these θ and EC sensors raise the possibility of automating not only irrigation, but also fertilizer applications. Integrated control of irrigation and fertilization is especially important in greenhouses, since water-soluble fertilizer is generally applied together the irrigation water. Furthermore, excess irrigation can was nutrients out of the substrate and thus reduce nutrient availability. Thus, there is an intrinsic link between irrigation and fertilizer management in greenhouses.

The purpose of this paper is not to provide to provide an exhaustive review of greenhouse irrigation and fertilization research, but rather to provide an overview of the research being conducted at the University of Georgia into automation of irrigation and fertigation in greenhouses. Past and ongoing research is described here using summaries from three studies with different objectives. Study 1 looked at the

effect of θ on the growth and water use of petunia (*Petunia* x *hybrida*) and how that water use is affected by plant age and environmental conditions. The second study explores the physiological responses of plants to different θ levels, in an attempt to explain how θ affects growth of annual vinca (*Catharanthus roseus*). Finally, the third study discusses recent efforts in controlling both θ and EC using *in situ* sensors.

Study 1: Automated control of substrate water content and its effect on growth and water use of petunia

Soil moisture sensor controlled irrigation allows for precise control of θ (Nemali and van Iersel, 2006), and thus allows for the quantification of the effects of θ on plant growth. At the same time, by monitoring how much water us required to maintain a stable θ, it is possible to determine the evapotranspirational water loss from the plants. Such information can be used to precisely quantify crop water requirements, information that has been lacking for ornamental greenhouse crops. Therefore, the objectives of this study were to 1) determine the effects of different θs on the growth and water relations of petunia (*Petunia* × *hybrida*) and 2) to quantify the daily water use of petunias as they develop from seedlings to salable plants.

Materials and Methods

Plant material and growing conditions. Containers were filled with 10 L of a peat (60%) - perlite (40%) substrate (Fafard 2P, Fafard, Agawam, MA). Twenty four petunia 'Velvet Carpet' seedlings grown in 512-cell plug flats were transplanted into each container and watered in. The substrate was well-watered during the first nine days after transplanting to allow the seedlings to establish. At each irrigation throughout this study plants were watered with a water-soluble fertilizer solution at a N concentration of 200 $mg \cdot L^{-1}$ using a fertilizer injector .

Treatments. After plants were established, irrigation was controlled by an automated irrigation controller similar to the one described by Nemali and van Iersel (2006). Two capacitance sensors (EC-5, Decagon, Pullman, WA, USA) were inserted into the substrate in each container. The sensors were measured every 20 minutes using a datalogger (CR10, Campbell Scientific). Voltage readings from the soil moisture sensors were converted to θ ($m^3 \cdot m^{-3}$) using our own substrate-specific calibration (θ = voltage × 1.7647 - 0.4745, r^2 = 0.95). The readings from the two sensors in each container were then averaged, and the datalogger subsequently compared the average θ in each container with the θ threshold for that particular container. As soon as the average θ in a container dropped below the threshold for irrigation, the datalogger opened an irrigation valve for 1 min, applying 63 mL of fertilizer solution to the container. Irrigation thresholds were θ-values of 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, and 0.40 $m^3 \cdot m^{-3}$.

Data collection. In addition to measuring θ and controlling irrigation, the datalogger stored the θ readings from each sensor every two hours and counted the number of times each container was irrigated. This allowed us to calculate the number of irrigations each container received each day, and thus the daily irrigation volume. At the end of the experiment, the shoots were cut off at the substrate surface and dried for 1 week at 80 °C, after which their dry weight was determined. Environmental conditions including photosynthetic photon flux were collected throughout the study and *PPF* was used to calculate the daily light integral (DLI, total amount of *PPF* received during a day).

Experimental design and data analysis. The data were analyzed using regression analysis. To quantify the effects of plant age and DLI on daily irrigation volume, multiple regression was used to fit the following equation: daily water use = a_0 + a_1×DLI + a_2×time, where a_0, a_1, and a_2 are regression coefficients, and time is the

number of days since the start of the treatments. Only the data from the treatment with a θ threshold of 0.40 $m^3 \cdot m^{-3}$ were used because this treatment had the highest water use and the regression equation therefore describes the maximum amount of water that is used by these plants.

Results and Discussion

The automated irrigation system generally was able to maintain θ close to the θ threshold (Fig. 1). It took 9 d from the start of the treatments for the substrate to dry out to the lowest θ threshold (0.05 $m^3 \cdot m^{-3}$). From day 13 to 15, θ in one of the two plots with θ thresholds of 0.30 $m^3 \cdot m^{-3}$ greatly exceeded the threshold. This was caused by heavy rain on day 13, which caused water to leak through the greenhouse glazing and drip into that particular tray.

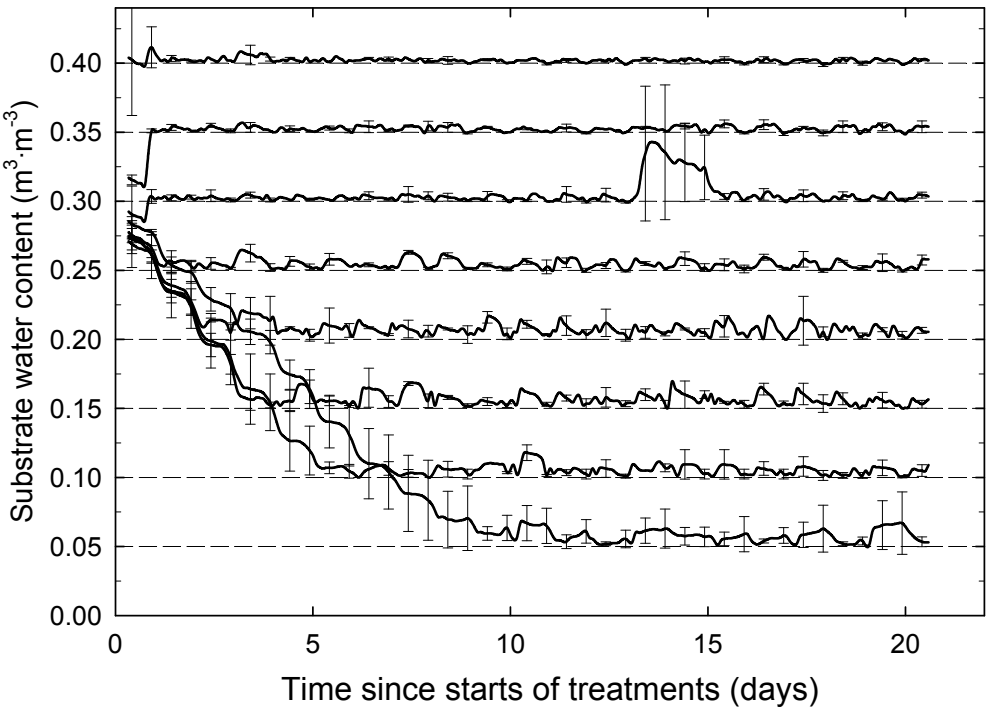


Fig. 1. Average substrate volumetric water content (θ) as maintained by a soil moisture sensor-controlled automated irrigation system. Dashed lines indicate the θ threshold at which the containers in the various treatments were irrigated.

The total amount of water applied during the treatment period increased linearly with increasing θ, from approximately 80 mL/plant in the 0.05 $m^3 \cdot m^{-3}$ treatment to 610 mL/plant in the 0.40 $m^3 \cdot m^{-3}$ treatment (Fig. 2). None of the applied irrigation water leached from the containers in this experiment.

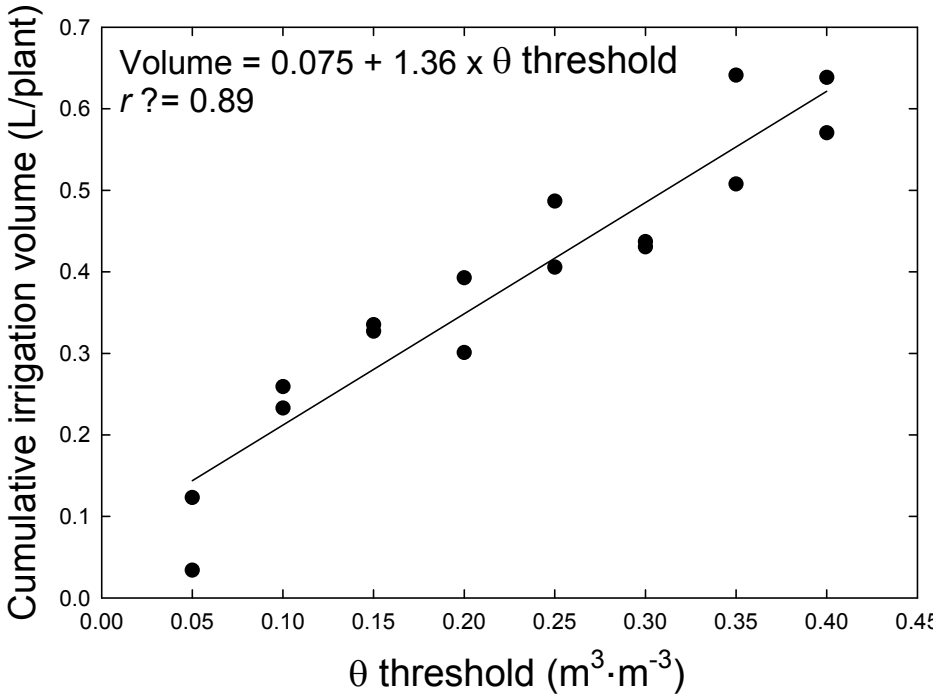


Fig. 2. Cumulative irrigation volume during the 22 d experiment, as a function of the substrate volumetric

The daily irrigation volume in the 0.40 $m^3 \cdot m^{-3}$ treatment was 12 – 20 mL/plant during the first week, and increased to a maximum of 44 mL/plant near the end of the experiment. As was the case with the total amount of water applied during the entire treatment period (Fig. 2), the daily irrigation volume increased with increasing θ thresholds (Fig. 3, bottom). In addition, irrigation volume in all treatments tended to increase during the experiment, likely because older, larger plants use more water. However, there were large daily fluctuations in the amount of irrigation water applied,

which were correlated with changes in DLI. For example, irrigation volumes were low on day 7 and 14, when DLI was low (Fig. 3). Using the data from the 0.40 $m^3 \cdot m^{-3}$ treatment for multiple regression confirmed that both time and DLI were positively correlated with daily irrigation volume. The regression equation [daily irrigation volume (mL/plant) = -7.15 + 1.14 × DLI + 1.54 × time, $r^2 = 0.79$] indicates that water use of the plants increased by 1.54 mL/d over the course of the study and by 1.14 mL/d for each additional $mol \cdot m^{-2}$ of *PPF*. This suggests that it may be possible to use

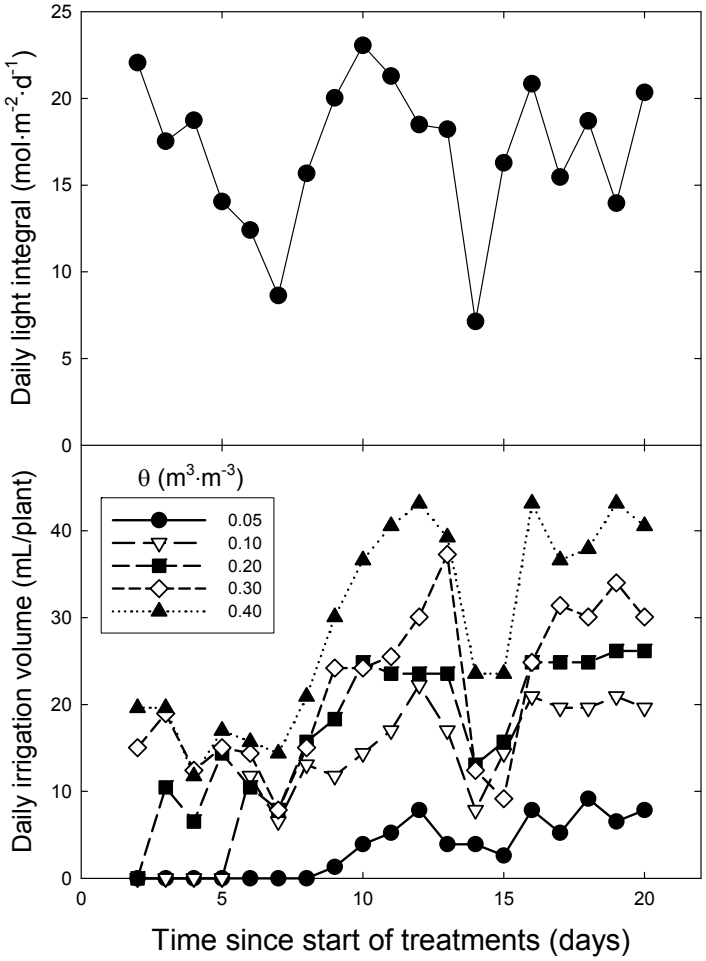


Fig. 3. Daily light integral (top) and daily irrigation volume (bottom) for petunias irrigated with a soil moisture sensor-controlled irrigation system. Substrate volumetric water content (θ) thresholds ranged from 0.05 to 0.40 $m^3 \cdot m^{-3}$. Daily irrigation volumes of only five of 8 treatments are shown for clarity.

relatively simple models to predict the water needs of floricultural crops. Similarly, daily water use of abutilon (*Abutilon* × *hybridum*) and lantana (*Lantana camara*) was strongly correlated with plant age and DLI (Kim and van Iersel, 2009). In Kim and van Iersel's study (2009), the daily maximum vapor pressure deficit also was correlated with daily water use, although not as strongly as either DLI or plant age. Overall, daily water use of abutilon and lantana could be accurately described as a function of time, DLI, and vapor pressure deficit (r^2 = 0.94; Kim and van Iersel, 2009). However, in both Kim and van Iersel (2009) and the current study, the data reflect the actual irrigation volume versus the predicted irrigation volume of the same plants (Fig. 4); *i.e.*, the predictions of daily water needs were not evaluated with an independent data set. For a more definitive evaluation of simple regression models to predict plant water needs, it will be necessary to grow plants for model development separate from those to be used for model evaluation to assure that the two data sets are independent (Wallach, 2006). Until such studies have been conducted, simple descriptive models like this should not be used to automate greenhouse irrigation. We are currently further pursuing this research.

There was a quadratic relationship between the θ threshold and shoot dry weight; as the threshold increased from 0.05 to 0.25 $m^3 \cdot m^{-3}$, shoot dry weight increased from approximately 0.7 g/plant to 1.7 g/plant. There was little additional increase in dry weight as the θ threshold further increased to 0.40 $m^3 \cdot m^{-3}$ (Fig. 4, left).

There was a linear relationship between the total irrigation volume and shoot dry weight (Fig. 4, right). The slope of the regression line is a measure of water use efficiency: for every liter of water applied an additional 2.54 g of shoot dry weight was produced; conversely, 394 mL of water was used for the production of 1 g shoot dry mass. Unlike most measures of water use efficiency, the slope of this regression line accounts for both evaporation from the substrate and transpiration from the plants.

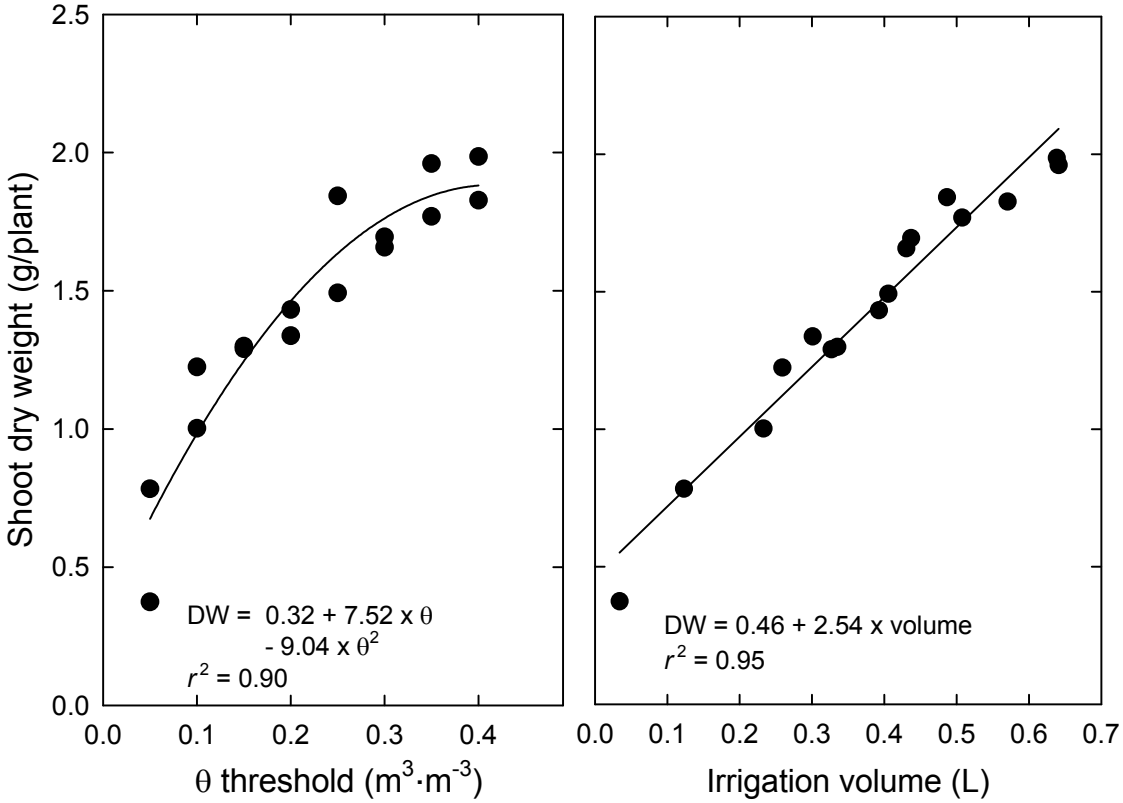


Fig. 4. Shoot dry weight (DW) of petunias irrigated with a soil moisture sensor-controlled automated irrigation system as a function of the substrate water content (θ) threshold (left) or total irrigation volume since the start of the irrigation treatments (right).

Study 2: Effects of substrate water content of growth and physiology of vinca (*Catharanthus roseus*)

The previously described study with petunia showed that differences in θ can have a pronounced effect on plant growth, but that study did not explore underlying physiological mechanisms that may cause these differences in growth. The objective of this research was to quantify growth and physiological responses of annual vinca (*Catharanthus roseus*) to different substrate water contents.

Materials and Methods

Plant material and treatments. Plug seedlings of vinca 'Titan Burgundy' were obtained from a commercial seedling producer and 24 seedlings were transplanted into containers (30 cm × 46 cm × 17 cm) filled with 10 L of a peat-perlite 60/40 v/v) growing medium (Fafard 2P; Fafard, Anderson, SC). At each irrigation plants were watered with a water-soluble fertilizer solution with a N concentration of 200 $mg \cdot L^{-1}$. To allow the seedlings to establish, the plants were kept well-watered (θ at least 0.47 $m^3 \cdot m^{-3}$) for one week, after which the plants were irrigated based on the θ. All plots were water using a soil moisture sensor-based, automated irrigation system, similar to that described for the petunia study. The set points for irrigation in this study were 0.05, 0.11, 0.17, 0.23, 0.29, 0.35, 0.41, or 0.47 $m^3 \cdot m^{-3}$.

Measurements. Leaf gas exchange parameters (transpiration rate, net photosynthesis, and stomatal conductance) were measured 35 d after the start of the treatments, and 7 d after the 0.05 $m^3 \cdot m^{-3}$ treatment had reached its set point, using a leaf photosynthesis system. Instantaneous water use efficiency was determined as the ratio between net photosynthesis and transpiration.

Leaf water and osmotic potential were measured using leaf cutter psychrometers at 22, 31, and 41 d after the start of the treatments. Turgor potential was measured as the difference between water and osmotic potential.

At the end of the study, 41 d after the start of the treatments, the area of the uppermost, fully expanded leaf of each plant was measured after which the shoots were cut off at the substrate surface and dried at 80 °C, after which shoot dry weight was determined.

Experimental design and statistical analysis. The experimental design was a randomized complete block with 8 treatments (θ set points) and two replications. Data were analyzed using regression analysis. An initial ANOVA indicated that there was no interaction between measurement day and treatment for either leaf water, osmotic, or turgor potential. Data were then averaged over the three measurements dates before further analysis.

Results and Discussion

As in the previously discussed petunia study, the irrigation system was able to maintain θ close to the set points. It took approximately three weeks for the substrate to dry to a water content of 0.05 m^3/m^3, but after the target substrate water content was reached, the water content remained stable throughout the experiment (Fig. 5).

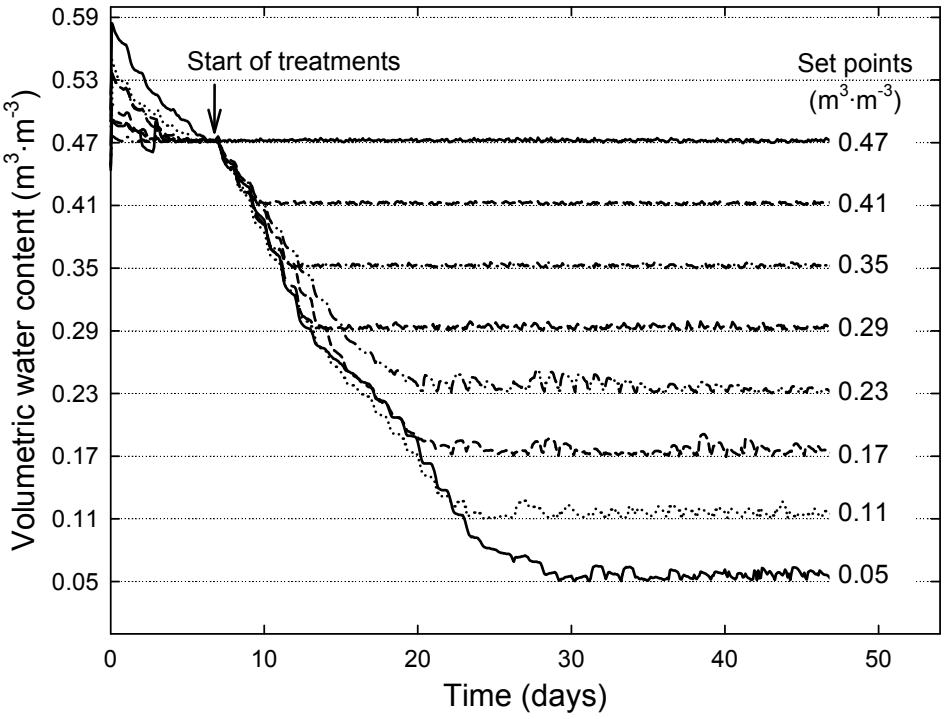


Fig. 5. Substrate water content throughout a seven week production period of annual vinca. Plants were watered only when the measured substrate water content dropped below the set point.

Plant growth was strongly correlated with θ. The shoot dry weight ranged from 0.6 g/plant at a θ of 0.05 m^3/m^3 to 1.8 g at a θ of 0.47 m^3/m^3 (Fig. 6, top).

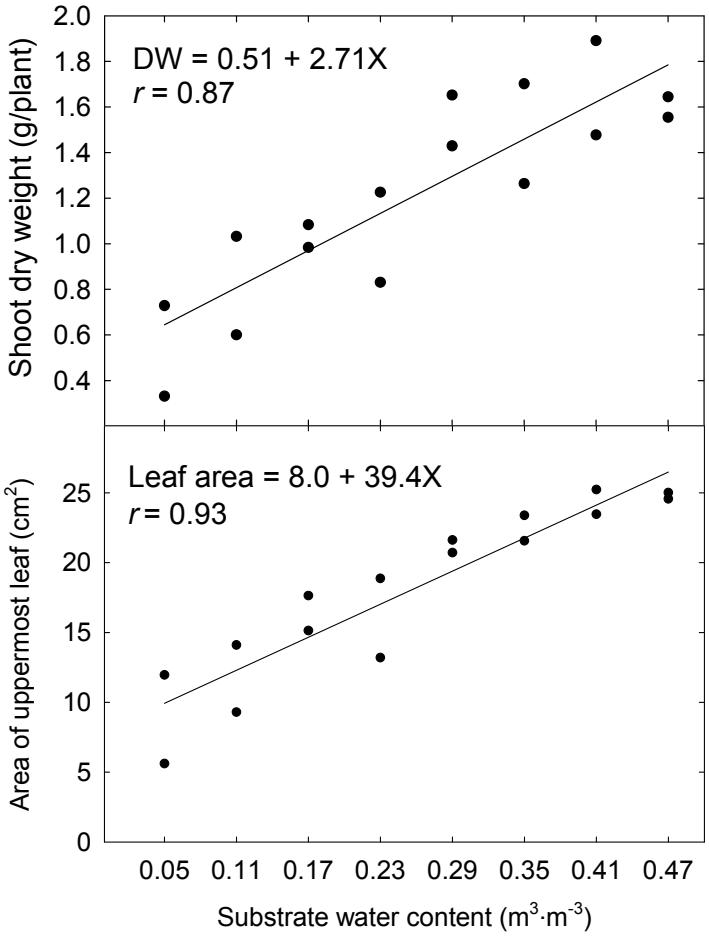


Fig. 6. The correlation between substrate water content and shoot dry weight (DW) (top) and the area of the uppermost fully expanded leaf (bottom) of vinca.

There also was a strong correlation between θ and the area of the uppermost fully expanded leaf, indicating that low θ inhibits leaf elongation. We did not find any evidence that this decrease in leaf elongation at low θ was due to low turgor in the leaves, since turgor potential was not affected by θ. This suggests that the decrease in leaf elongation instead may have been related to a change in cell wall properties. Both water and osmotic potential were decreased at low θ (Fig. 8).

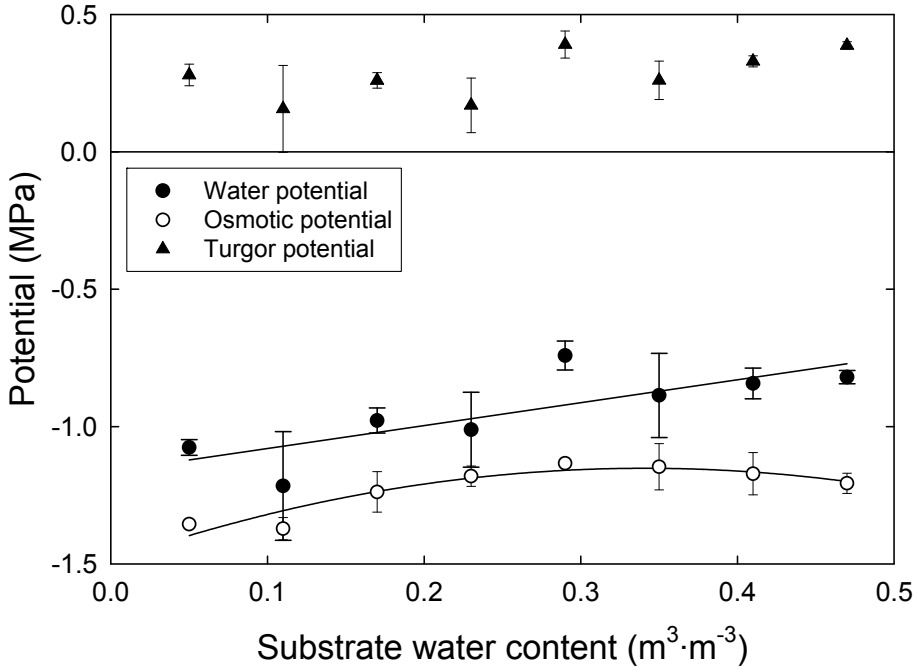


Fig. 7. The effect of substrate water content on the leaf water, osmotic, and turgor potential of vinca.

Leaf gas exchange data indicated decreased transpiration and stomatal conductance at low θ, but there was no significant effect on leaf photosynthesis (Fig. 8). The combined effects on transpiration and photosynthesis resulted in an increase in water use efficiency at low θ. Our finding that θ had no effect on leaf photosynthesis was a particularly interesting, since low levels of θ did reduce growth. Apparently this growth reduction was not due to decreased leaf photosynthesis. As a matter of fact, there was no correlation between leaf photosynthesis and plant dry weight (P = 0.49). Although this may seem surprising, it has long been known that there often is little or no correlation between leaf photosynthesis and plant growth (Evans, 1975). The main reasons for this are that leaf photosynthesis measurements do not take into account the total photosynthetically-active leaf area, the efficiency of conversion of photosynthates into dry matter, or the dry matter distribution within the plant (van Iersel and Bugbee, 2000).

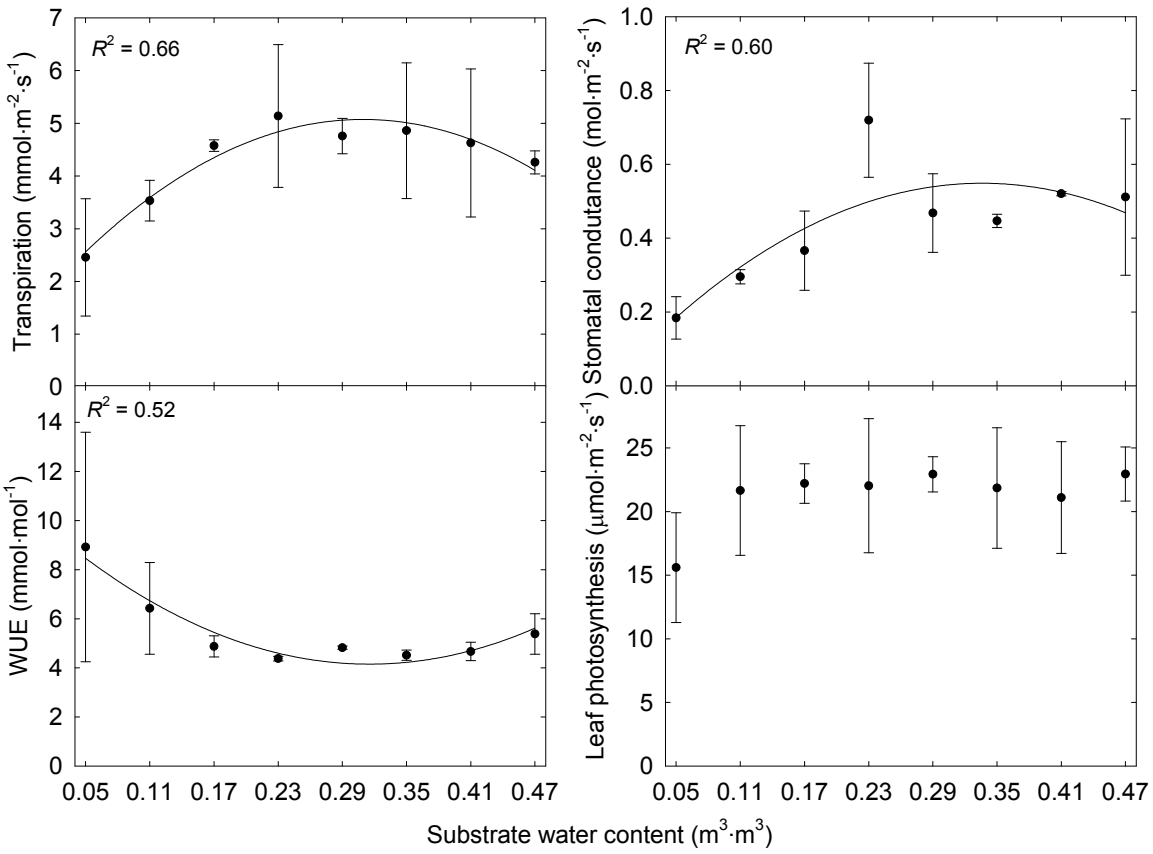


Fig. 8. The effect of substrate water content on transpiration, stomatal conductance, instantaneous water use efficiency, and photosynthesis of vinca leaves. Curves indicate statistically significant effects ($P < 0.05$). There was no significant effect on leaf photosynthesis ($P = 0.16$).

Unlike leaf photosynthesis, leaf area was strongly correlated with shoot dry weight ($r = 0.96$). These results suggest that decreased growth under drought stress was primarily the result of smaller leaves, and thus less photosynthetically active tissue, rather than decreases in the photosynthetic rate per unit leaf area. Likewise, we have seen that the growth of salt-stressed tomato plants also was better correlated with the area of the uppermost, fully-expanded leaf than with leaf photosynthesis (Montesano and van Iersel, 2007).

Overall, results from this study suggest that drought stress reduces growth, but that such growth reductions can occur without a significant reduction in growth. Instead the cause of the growth reductions appears to an inhibition of leaf elongation by drought stress, thus resulting in small leaves and less photosynthetically active tissue. The cause of the reduction in leaf elongation may a change in cell wall plasticity, rather than a decrease in turgor pressure.

Study 3: Automated Control of Water Content and Electrical Conductivity in Soilless Substrates: Proof of Concept

The first two studies clearly show that controlling irrigation with soil moisture sensors is feasible. However, irrigation and fertilization are close related processes in greenhouses, since the fertilizer generally is applied along with the irrigation water. The next step in this research therefore is to control both irrigation and fertilization by measure θ and electrical conductivity (EC) of the substrate. Electrical conductivity (EC) can be used as an indicator of the total amount of soluble salts in the substrate, and as such is commonly used as a proxy for nutrient availability. Recently, new sensors (5TE, Decagon Devices, Pullman, WA) have become available that can measure both the VWC and EC of soilless substrates. EC measurements are taken using two small stainless steel screws embedded in the sensor. These screws serve as the electrodes for the EC measurements. Thus, EC measurements using these sensors reflect the bulk EC of the substrate; i.e., these measurements reflect how well the substrate as a whole (including the solid substrate components, the pore water in the substrate, and the air in the substrate) conducts electricity. However from a plant's perspective, it is more relevant to determine the EC of the pore water. Hilhorst (2000) described a model that allows the estimation of pore water EC from measurements of bulk EC, temperature and the real portion of the dielectric permittivity of the substrate (ε_b) which is measured by the sensors. The objective of this study was to determine

whether these 5TE sensors can be used to control both the water content and the EC of soilless substrates.

Materials and Methods

An automated irrigation and fertigation system was built using 16 5TE sensors connected to a datalogger (CR10X, Campbell Scientific, Logan, UT), using a multiplexer (AM16/32, Campbell Scientific) (Fig. 1). Sensor readings of ε_b were converted to the volumetric water content (VWC) of the substrate, using our own calibration for the peat-perlite mix used in this study (VWC = $-0.0387\times\varepsilon_b^2 + 3.4436\times\varepsilon_b - 4.1848$, $R^2 = 0.99$; VWC is expressed here as % water content and was subsequently converted to units of m^3/m^3 by dividing by 100). Bulk EC, temperature, and ε_b measurements were used to calculate pore water EC, using Hilhorst's equation (Hilhorst, 2000), with an offset value (dielectric permittivity of the dry substrate) of 1.55.

The datalogger determined whether the measured VWC was below the VWC set point for a particular plot. If so, the datalogger then compared the calculated pore water EC to the EC set point. If the pore water EC was above the EC set point, the plants were irrigated with tap water, otherwise the plants were fertigated with a fertilizer solution with an EC of approximately 10 mS/cm. Such a high fertilizer EC was needed to see a detectable increase in pore water EC. The datalogger activated solenoid valves to either irrigate or fertigate each group of plants using two relay drivers (SDM16ACDC, Campbell Scientific). To achieve this, two separate irrigation systems were built, one that provided plants with tap water and another one that provided plants with fertilizer solution (Fig. 9). The plants were irrigated/fertigated using drip emitters connected to pressure compensated emitters (2 lph, Netafim, Tel Aviv, Israel). Each time the irrigation/fertigation for a particular plot was activated,

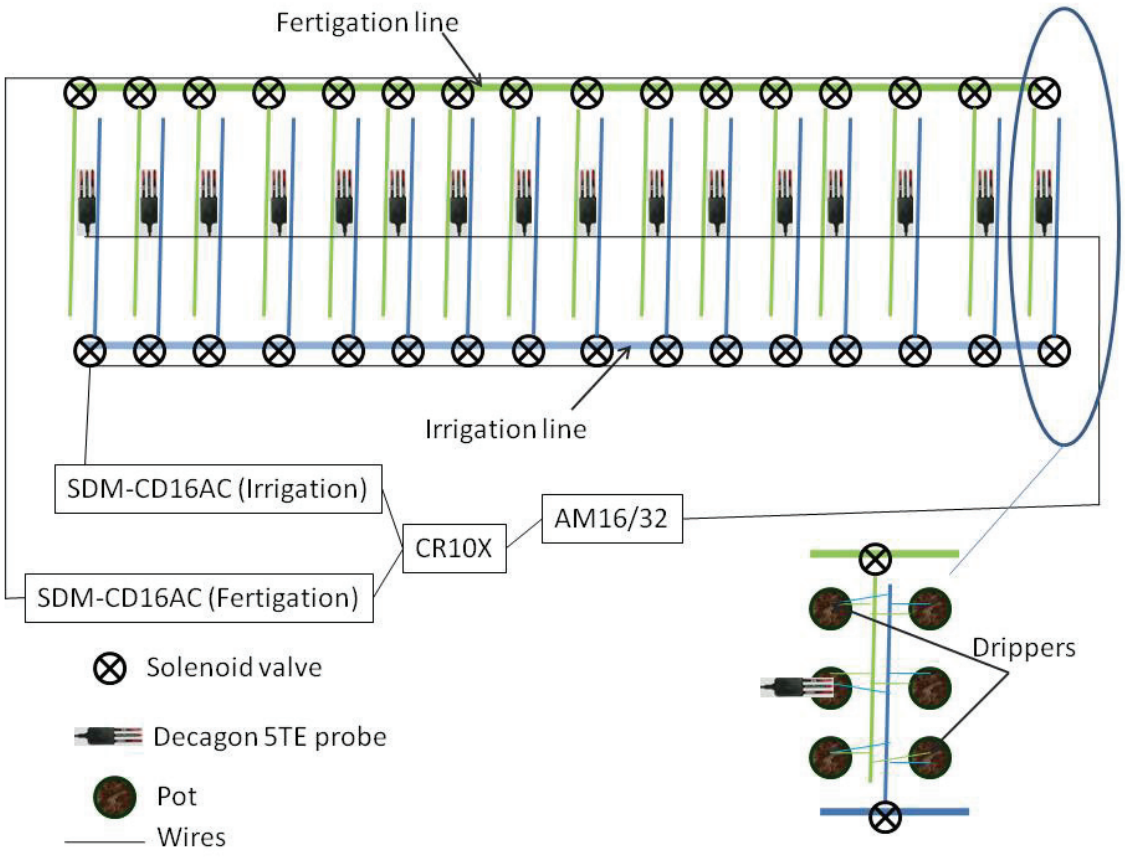


Fig. 9. Diagram of the sensor-controlled irrigation and fertigation system. The CR10X datalogger measures the water content and EC of the substrate using 5TE sensors and then determines whether to irrigate or fertigate a particular plot. Solenoid valves are activated using two relay drivers (SDM16ACDC). Only one out of six pots in each plot has a 5TE sensors. Irrigation and fertigation of all six plants in a plot are controlled based on the readings from that one sensor.

the solenoid valve opened for 30 s, thus applying approximately 16.5 ml per irrigation/fertigation event.

To test the automated irrigation and fertigation system, 96 ornamental cabbages (*Brassica oleracea)* were planted in 6" pots filled with a peat-perlite substrate (Fafard 2P, Agawam, MA, USA). The plants were arranged in 16 plots of 6 plants each, and a 5TE sensor was inserted into one of the six pots within each plot. The datalogger

was programmed to maintain the substrate water content at 0.25, 0.30, 0.35, or 0.40 m^3/m^3 and the pore water EC at 1, 2, 3, or 4 mS/cm in a factorial arrangement, thus resulting in 16 treatments. Due to the malfunctioning of one sensor, there are no data from the treatment with set points of 0.40 m^3/m^3 and 3 mS/cm. The shoots of the plants were harvested at the end of the study for dry weight measurements after 35 days.

Results and Discussion

Control of substrate VWC was good, with substrate VWC generally within 0.03 m^3/m^3 of the set point (Fig. 10). Control of pore water EC was more difficult, and there were large fluctuations in pore water EC, especially during the first 20 days of the experiment. Several factors contributed to the pore water EC fluctuations. 1) No control of pore water EC was possible until after the VWC of the substrates had reached the VWC set point, since plants were not irrigated or fertigated until this set point was reached. 2) The small screws that serve as EC sensors on the 5TE results in less than optimal contact between the electrodes and the substrate (or pore water). If there is an air pocket surrounding one of the electrodes, the measured bulk EC is low, resulting in a low calculated pore water EC as well. Good contact between the electrodes and the substrate is critical for the bulk EC measurements. Sensors with a different design, including larger electrodes, might therefore work better. 3) The calculated pore water EC depends on the VWC of the substrate, resulting in rapid changes in pore water EC following an irrigation or fertigation event. In addition, as the substrate dries out following irrigation, the pore water EC increases because the solution becomes more concentrated as the amount of water decreases. 4) There is no verification of how accurately the Hilhorst model determines the pore water EC, and recent research has suggested that the Hilhorst model may not be very accurate in soilless substrates (Arguedas Rodriguez, 2009). In addition, the correct offset value in

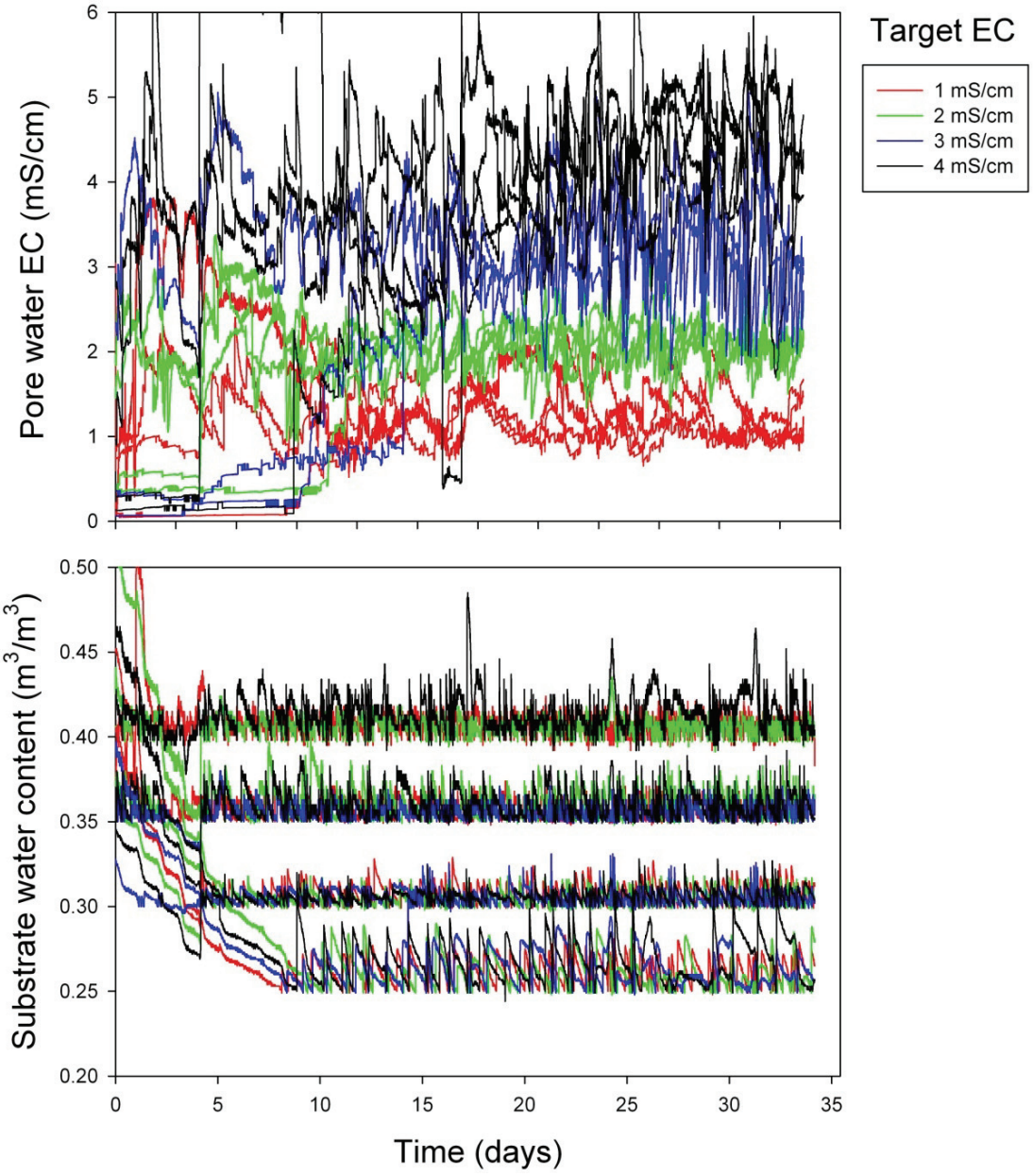


Fig. 10. Pore water EC (top) and water content (bottom) of the substrate throughout the experiment. Set points for pore water EC were 1, 2, 3, and 4 mS/cm, and those for substrate water content were 0.25, 0.30, 0.35, and 0.40 m^3/m^3. Note that control of substrate water content was better than control of pore water EC.

the Hilhorst model is not clear. More work is needed on how to determine pore water EC. 5) Fertilizer appears to move much more slowly through the substrate than water. Preliminary data showed that applying very small amounts of water (5.5 ml/plant) at a time resulted in increases in measured VWC, but not EC. Fertilizer concentrations were much higher at the location of the emitter applying the fertilizer solution than in the rest of the substrate. It may take several irrigation/fertigation events to move this fertilizer further into the substrate, where it can be measured by the EC sensor. To address this problem, we increased the amount of water applied at each irrigation, sacrificing some precision in control of VWC. Despite these issues, there were clear differences in the pore water EC among the different EC set points, and this was most evident during the last 15 days of the study. This suggests that the use of EC sensors for fertigation control is possible, but better sensors may be needed to get better measurements and control of pore water EC.

Depending on the treatment, the plants received between 0.14 and 3.6 liters of water and 0.26 and 1.15 liters of fertilizer solution during the 35-day experiment. For example, the plants in the treatment with set points of 1 mS/cm and 0.40 m^3/m^3 received 0.40 liters of fertilizer solution and 3.6 liters of water, while set points of 4 mS/cm and 0.30 m^3/m^3 resulted in applications of 1.15 liters of fertilizer solution and 0.35 liters of water during the experiment.

Both VWC and pore water EC set points affected the growth of the plants (Fig. 11). Shoot dry weight decreased as the set point for pore water EC increased. Shoot dry weight also was reduced by low set points for VWC, while shoot dry weights were similar with set points of 0.35 and 0.4 m^3/m^3. Such effects of VWC on plant growth are consistent with earlier findings (Burnett and van Iersel, 2008).

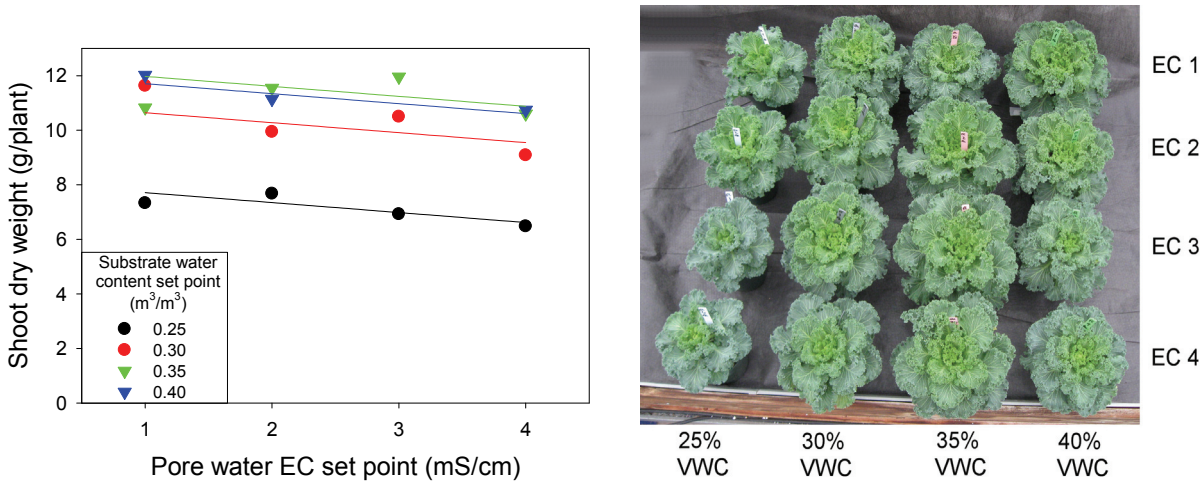


Fig. 11. The effect of set points for substrate volumetric water content (VWC) and pore water EC on the shoot dry weight of ornamental cabbage. There was a linear effect of pore water EC and a quadratic effect of substrate volumetric water content on shoot dry weight, but no interactive effect between pore water EC and VWC (Dry weight = - 30.5 - 0.366×EC + 234×VWC - 320×VWC^2, R^2 = 0.92, P < 0.0001). Representative plants from each treatment are shown on the right.

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