Efficient Irrigation Management Tools for Agricultural Cultivations and Urban Landscapes

IRMA

Experiments regarding use of saline water for cultivation in greenhouse.

WP6, Action 6.5.

Deliverable 6.5.3

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Deliverable 6.5.3. Research report on experiments regarding the use of saline water for cultivations in greenhouse.

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Efficient Irrigation Management Tools for Agricultural Cultivations and Urban Landscapes (IRMA)

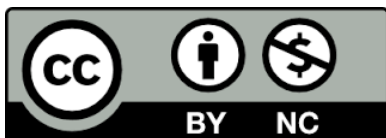# Publication info

WP6: Specialized research actions

Deliverable 6.5.3 Research report on experiments regarding the use of saline water for cultivations in greenhouse.

Contents

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Foreword

This report contains a description of the activities carried out by CNR-ISPA (P4) in the framework of WP6 - Specialized research actions, Deliverable 6.5.3 - Experiments regarding the use of saline water for cultivations in greenhouse.

The activities focused on testing sensor-based irrigation management strategies in greenhouse in saline conditions, with the aim to provide tools for irrigation decision and rational leaching control. We implemented both laboratory and on-field activities, focusing on tomato as the most important greenhouse vegetable crop in Mediterranean environment.

Beside an introductive examination of the state of the art and of the concepts at the base of the carried out activities, a description of the experiments and of the results is included in this report.

We outline that the full dataset from the experiments is at the moment under use or consideration for publication in scientific international journals, with the aim to present the outcomes of the IRMA project to the wide scientific community. Therefore, in order to be compliant with the universal requirement for scientific publication (the material should not have been previously published elsewhere, except in a preliminary form) we will not include in this report the full set of data; however, we will give anyway an exhaustive overview of the findings of the project activities.

All the publications that will arise from the activities carried out in the project will clearly refer to the IRMA project as source of funding for the conducted research.

Introduction

The increasing demand for water uses other than agricultural will force agriculturists to manage irrigation water efficiently, contributing to environmental preservation. In parallel, brackish and saline water resources use for irrigation could be increased if greater knowledge of salt tolerance and proper technologies are developed. In applying saline/brackish water for irrigation, an integrated approach, which should account for soil, crop and water management at the same time, should be adopted. This approach needs knowledge of crop water requirements which are essential for water saving, controlling water table level and drainage volume, and of course the final yield (Reina-Sànchez et al., 2005).

Large areas of Mediterranean Basin are affected by the scarcity of good quality water. In coastal areas, where vegetable greenhouse industry is more developed, moderate saline water is generally available and used for irrigation.

Vegetable crops are generally sensitive or moderately sensitive to salinity, and yield reductions are expected with moderate levels of salinity in the root-zone solutions (Maas and Hoffman, 1997).

Production of horticultural crops in greenhouses has expanded considerably over recent decades in Mediterranean areas (Sonneveld and Voogt, 2009). Tomato (Solanum lycopersicum L.) is the most important greenhouse vegetable crop grown in soilless cultivation systems (Savvas et al., 2013) in particular in Mediterranean Basin, where it is often cultivated in saline or poor-quality irrigation water. Saline water is used in cultivation mainly due to (i) limited availability of fresh water and (ii) improvement in fruit quality associated with moderate salt stress (Sakamoto et al., 1999; Serio et al., 2004; Montesano et al., 2010).

Soilless culture is considered one of the main components of sustainable protected horticulture. In fact, the application of closed growing systems, where the drainage water is captured and reused after nutrient replenishment, can reduce the consumption of water and fertilizers and the environmental pollution that are generally associated to over-irrigation (Massa et al., 2010). However, although in particular productive areas the adoption of closed-cycle is a well-established practice (e.g. the Netherlands), commercial application of these systems is scarce in areas with low-technology greenhouses (such as the Mediterranean basin), as their management is more complex compared with open (free-drainage) cultivation systems (Pardossi et al., 2005; Massa et al., 2011). The difficulties in the implementation of closed cycle soilless cultivation is increased when saline water is used for irrigation.

Often the use of saline water has been associated to the soilless cultivation, as a solution to the long-term salinization of soils. The most largely adopted practice in this conditions is the adoption of open cycle cultivation on mineral substrates (perlite, rockwool) with high leaching fraction (up to 40-60%). The salt accumulation in the growing substrate can thus be prevented by leaching with extra irrigation water. However, this practice leads to high volume of water applied to increase the leaching fraction, and implies a high economic and environmental cost (Katerji et al., 2004; Valdès et al., 2014).

A conspicuous research activity has been focused on the adoption of semi-closed cycle, with periodical discharge of high EC nutrient solution into the environment. **However, open cycle is still the most used and feasible approach in Mediterranean greenhouse tomato industry, generally characterized by low technology. Thus, it is crucial to take advantage of the most promising technologies (i.e. sensors for the measurement of the water and EC status of substrates) to make the most possible efficient the cultivation techniques, and reduce the environmental impact resulting from the waste of water resources and the release of fertilizer solutions into the environment**.

A fundamental management consideration for soilless growing systems is the requirement to maintain the salinity of the root zone solution at levels not detrimental to optimal crop production (Sonneveld, 2000). An appreciable proportion of the applied nutrient solution is then drained to prevent salt accumulation. This represents both a substantial loss of water and a major source of pollution of groundwater (Magàn et al., 2008). However, to determine if leaching is really needed, it is necessary to measure the salt concentration in the root zone. To achieve this, detailed knowledge of the crop response to salinity is required. Also for tomato grown in open cycle soilless conditions, knowledge of the response to salinity is required to optimize yield and fruit quality (Magàn et al., 2008).

Among the different irrigation management approaches, the one based on the measurement of the growing media (soil or soilless substrates) water status represents probably the most directly applicable, since it is directly related to the water availability for plants. The use of sensors for the measurement of the growing media water status is able to overcome the approximation of mathematical models used to describe the dynamics of the water in the substrate – plant – atmosphere continuum – generally based on the relation between evapo-transpiration and environmental conditions - and to avoid laborious laboratory determinations, generally not applied in the production facilities.

The possibility to measure with sufficient accuracy the substrate water status, through using specific sensors, allows to set when and how much irrigation is required, which should take place when a threshold value is reached. Automation of irrigation can be obtained connecting moisture sensors to specific devices able to process the sensors output and decide when pumps should be switched on.

With this aim, **the availability on market of new sensors able to combine the measurement of the substrate water content and the electrical conductivity (EC) offers interesting possibilities for the irrigation management, and the salt accumulation and leaching control of soilless cultivation in saline conditions** (Incrocci et al., 2010).

TESTING APPROACHES TO ESTIMATE THE SALINITY STATUS OF SOILLESS GROWING MEDIA

In soilless greenhouse cultivation, irrigation is about water and salts (both fertilizers and salts originally present in the irrigation water, i.e. NaCl). In greenhouse industry, monitoring of salt accumulation in the growing substrate represents a key-factor to obtain optimal crop performances.

Excessive salinity in the root-zone usually has adverse effects on plants, which may suffer reduced and slowed growth, physiological damages and, in the severest cases, death. The mechanisms at the basis of these effects are related both to osmotic stress and ions toxicity, with sodium and chloride usually considered toxic to plants (Hasegawa, 2000).

Many detrimental effects of salt stress have been reported on tomato, mainly concerning reductions in yield (Cuartero and Fernandez-Munoz, 1999). Although saline conditions are linked to reductions in growth and yield, in some cases moderate salt stress can improve fruit quality (Cornish, 1992; Plaut, 1997; Sakamoto et al., 1999; Serio et al., 2004). In soilless cultivation, growers may increase the electrical conductivity (EC) of the nutrient solution by adding NaCl or by increasing the overall nutrient concentration to apply a controlled salt stress to the plant and increase fruit quality.

Salt accumulation in the growing media is also one of the variables that influence the irrigation management, since i) irrigation water not only applies water to plants and substrates, but also salts (both soluble fertilizers and/or salts present in the original composition of the irrigation water); ii) irrigation is generally used in soilless conditions to prevent salt excess through leaching.

In particular, the duration of an irrigation event is mainly dictated by the amount of water that needs to be supplied to the plant, plus any amount of leachate that is needed. The percentage of leachate in relation to the total amount of water applied is called the 'leaching fraction'. In conventional

irrigation approaches, the leaching fraction should range from 0 to 20 per cent under well-controlled conditions; in rare instances, greater percentages are targeted (i.e. when saline irrigation water are used) (Lieth and Oki, 2008). However, it is common in substrate systems to apply 30 - 50% more water than is used by the crop (Kläring, 2001), and often growers don't have a clear and precise record of the water actually lost as leaching.

The leaching fraction is typically a function of the degree to which salt-build-up is likely to be a problem. If the source water is somewhat saline and fertilizer salts are added to this water, then the salinity may well rise to a level where it is problematic to the plants. If this is the case, then the amount of leaching should be relatively high. Leaching may be desirable in cases where the water used for irrigation is low in quality, as it will ensure that salts that may accumulate are moved out of the root zone. If the water is of high quality and fertigation results in little build-up of salts in the root zone, then the leachate volume can be minimized (Lieth and Oki, 2008).

It is consequential that **measuring salinity of substrate is an essential task in order to apply leaching in a rational way**.

In the greenhouse industry, methods have been developed for the determination of the nutrient availability and salinity status of soils and substrates. A review is presented on the applications of the soil and substrate testing methods in relation to systems and growing conditions (Sonneveld and Voogt, 2009):

Situation	Before cultivation	During cultivation
Soil	1,2	1, 2
Natural organic substrate, pre-shaped	5,6	5, 6, 7+8
Natural organic substrate, loose	5,6	5, 6, 7+8
Rockwool (slabs and cubes)	6	3, 7+8
Foam (slabs and cubes)	6	3, 7+8
Rockwool and foam loose	6	7+8, 9
Course grained mineral substrates	6	7+8, 9
Fine grained mineral substrates	6	6, 7+8
Hydroponics (without any substrate)	-	10

Adapted from Sonneveld and Voogt, (2009)

1. Specific 1:2 volume extract

2. Saturation extract

3. Substrate solution by suction with a syringe in the field

4. Substrate solution by pressing at field capacity

5. 1:1.5 v/v extract

6. 1:5 v/v extract

7. Supplied nutrient solution

8. Drainage water

9. Supernatant solution on the bottom of plant container

10. Circulation nutrient solution

Recently, new sensors have become available that can measure both the volumetric water content (VWC) and EC of soilless substrates. VWC measurements with these sensors work the same as with other capacitance sensors that have been on market for several years and used successfully for irrigation control. The EC measurements using these sensors reflect the bulk EC (ECb) of the substrate (how well the substrate as a whole - the solid component, the pore water in the substrate and the air in the substrate – conducts electricity). However, for agronomic purpose, it is more relevant to determine the EC of the pore water (ECp).

A model for the estimation of ECp from measurements of ECb, temperature and the real portion of the dielectric permittivity of the substrate (ε) which is actually measured by the sensors is described by Hilorst (2000) (Miralles et al., 2010).

However, while the VWC measurements by these sensors have been proved to be reliable and suitable to be used for successful irrigation automation in greenhouse, the accuracy of in situ EC measurement using dielectric sensors in saline conditions is still problematic (Bittelli, 2011). According to several experiences, the Hilorst equation, generally proposed by sensors manufacturers to convert ECb into ECp, is not always able to perform this conversion in a reliable and accurate manner in the conditions typical of several growing systems used in greenhouse (i.e. soilless systems), due to salinity, temperature and substrate moisture fluctuations. Therefore, the possibility to use EC readings performed by FDR sensors available on market for automatic irrigation management of soilless greenhouse crops needs to be better investigated.

The IRMA case-study: sensor-based irrigation control of soilless tomato cultivation using saline water

A great number of studies on fertigation methods focus on controlling the drainage of the nutrient solution that is applied to the culture unit in vegetable soilless cultivation (Rodrìguez et al., 2014).

As previously outlined, several low-cost sensors are currently available on market with the ability to measure both VWC and EC in soilless growing substrates. This capability will potentially provide growers with an instantaneous and continuous indication of when salts (fertilizers and/or toxic salts i.e. NaCl) are under the recommended value for a specific crop or when their concentration is increasing in the root zone, leading to potential negative effects on plant growth. The ability to measure EC in real time using sensors, more cost-effective than the current labor-intensive methods used to monitor EC, may result in improved and more efficient irrigation scheduling, if EC measurements will be integrated in automatic irrigation decision processes.

A particular case in which the real-time continuous EC measurement of the substrate could be of great benefit is the cultivation of vegetables using saline water in soilless conditions. As explained before, in this condition applying a high leaching fraction is the common approach. However, according to our experiences, the leaching control may be improved by scheduling irrigation based on VWC+EC substrate sensors.

Based on this premise, we performed a study aimed to automate the irrigation control of a soilless tomato cultivation in saline conditions through a sensor-based approach.

The objectives of the study were:

- To test the performance in soilless (perlite) cultivation conditions using saline water of a recently available sensor, the GS3 (Decagon Devices, USA), a dielectric sensor which measure volumetric water content (VWC), temperature and bulk EC (ECb), and, accordingly to the manufacturer, is designed specifically for use in soilless growing media.

- To test the effects of increasing levels of fertigation control (timer- or sensor-based with measurement of only substrate VWC or combined measurement of VWC + EC) and salinity status of growing substrates in a open cycle soilless cherry tomato cultivation using moderate saline water (NS EC ≈4 dS/m), on the overall crop performance (water use, yield and quality) and physiological response of plants.

We hypothesized that, compared to a predetermined timer-based irrigation schedule approach, more efficient water usage could be obtained by real-time measurement of VWC, due to the constant determination of real plant water needs, and even more with combined measurement of VWC and EC, due to the possibility to control the leaching needs according to a desired substrate salinity level.

DESCRIPTION OF THE STUDY

The study was carried out in the greenhouse and laboratory facilities at the experimental farm "La Noria" (Mola di Bari, BA, Italy) of the Institute of Sciences of Food Productions - National Research Council (CNR – ISPA), in the period September 2014 – June 2015 (Picture 1)

Picture 1: Experimental station "La Noria", CNR – ISPA (Mola di Bari, BA, Italy).

The whole study was structured in two consecutive phases.

The Phase 1 had the specific objective to study the performance of the GS3 sensor when used in perlite, a typical soilless substrate largely adopted for the tomato soilless cultivation in Mediterranean environment, with a particular focus on the measurements of the substrate EC. This part of the study included both laboratory tests and observations in real cultivation conditions (see after for a detailed description).

The Phase 2 included the implementation of a six-months tomato cultivation trial in which different strategies for the automatic irrigation management were tested. The strategies based on the automatic sensor-based scheduling of fertigation were compared with a timer-based approach. In this study, we used a moderate saline water (≈ 1 g/L) for the preparation of the nutrient solution, and

we aimed to the rational control of water supply and leaching in order to manage the salinity build-up in the growing media.

PHASE 1

SUBSTRATE-SPECIFIC CALIBRATION OF GS3 SENSORS

The GS3 sensor uses an electromagnetic field to measure the dielectric permittivity of the surrounding medium. The sensor supplies a 70 MHz oscillating wave to the sensor prongs that charges according to the dielectric of the material. The stored charge is proportional to substrate dielectric and substrate volumetric water content. The GS3 microprocessor measures the charge and outputs a value of dielectric permittivity from the sensor. The dielectric value is then converted to substrate water content by a calibration equation.

A general calibration equation is provided by the manufacturer. However, to use growing-media specific calibration equations is recommended for better accuracy.

The substrate used in this study was the perlite. We selected a 1-2 mm grain-size perlite (Agrilit 2, Perlite Italiana, Italy). A moisture release curve analysis was performed in order to assess the tensiometric characteristics of the substrate in use. The analysis was performed using a HyProp system (UMS GmbH, Munich, Germany) and are reported in Fig. 1.
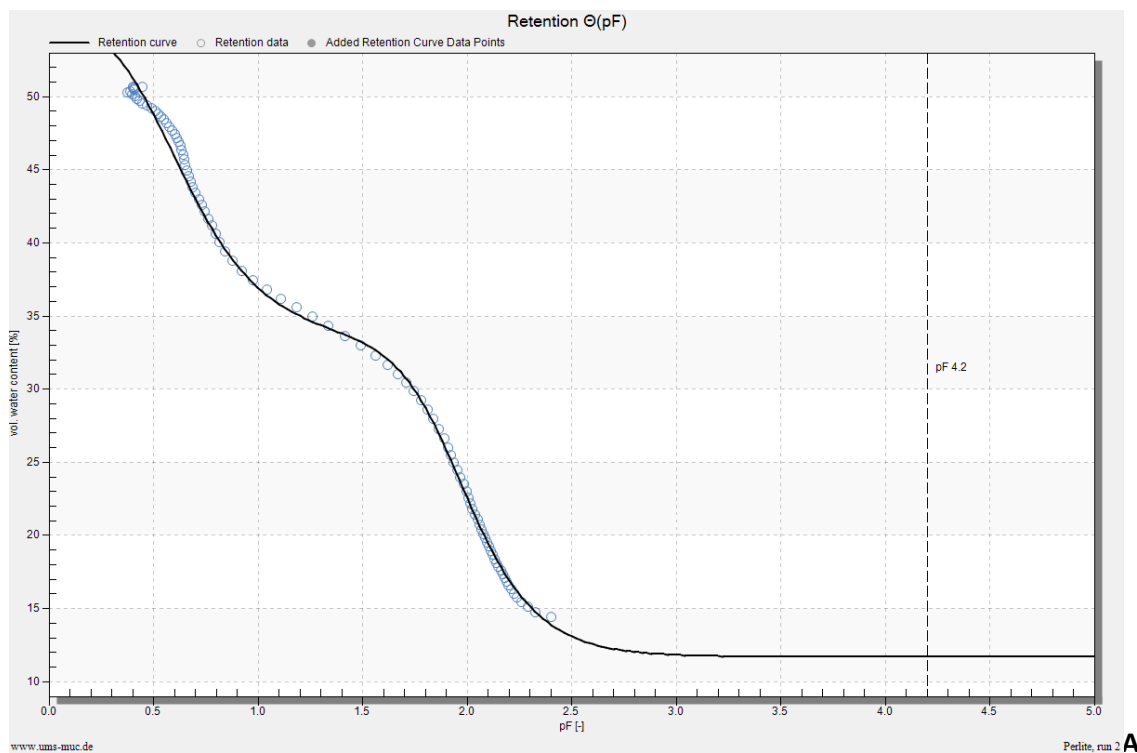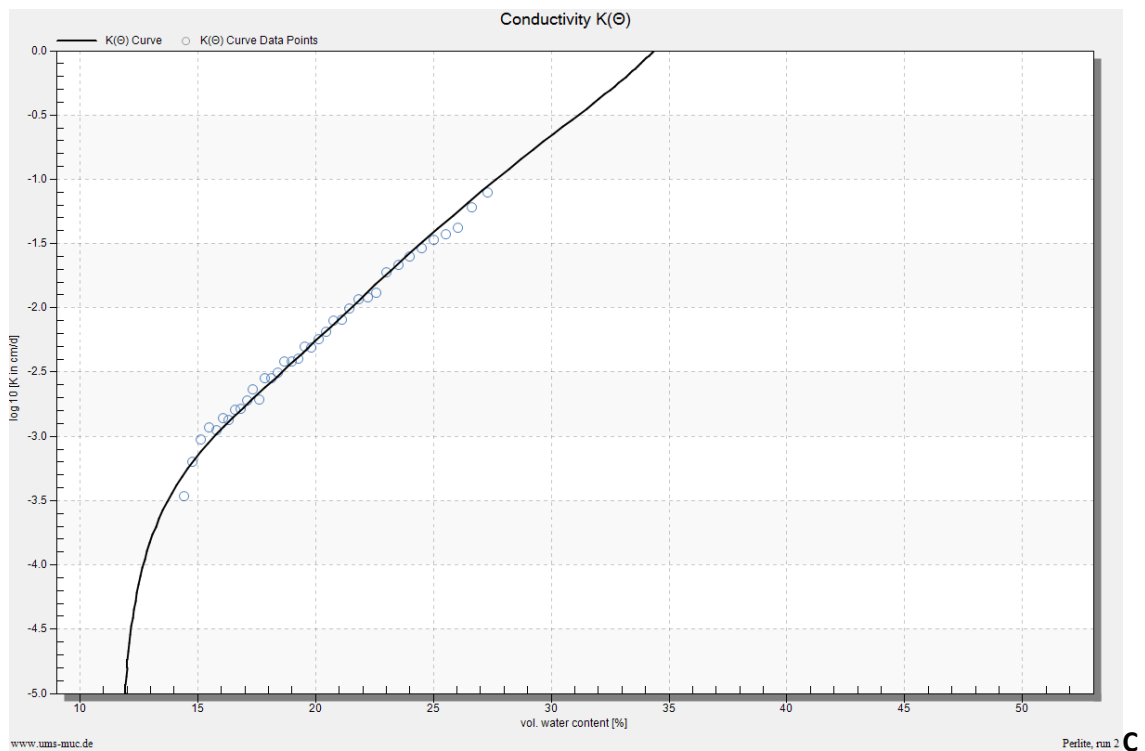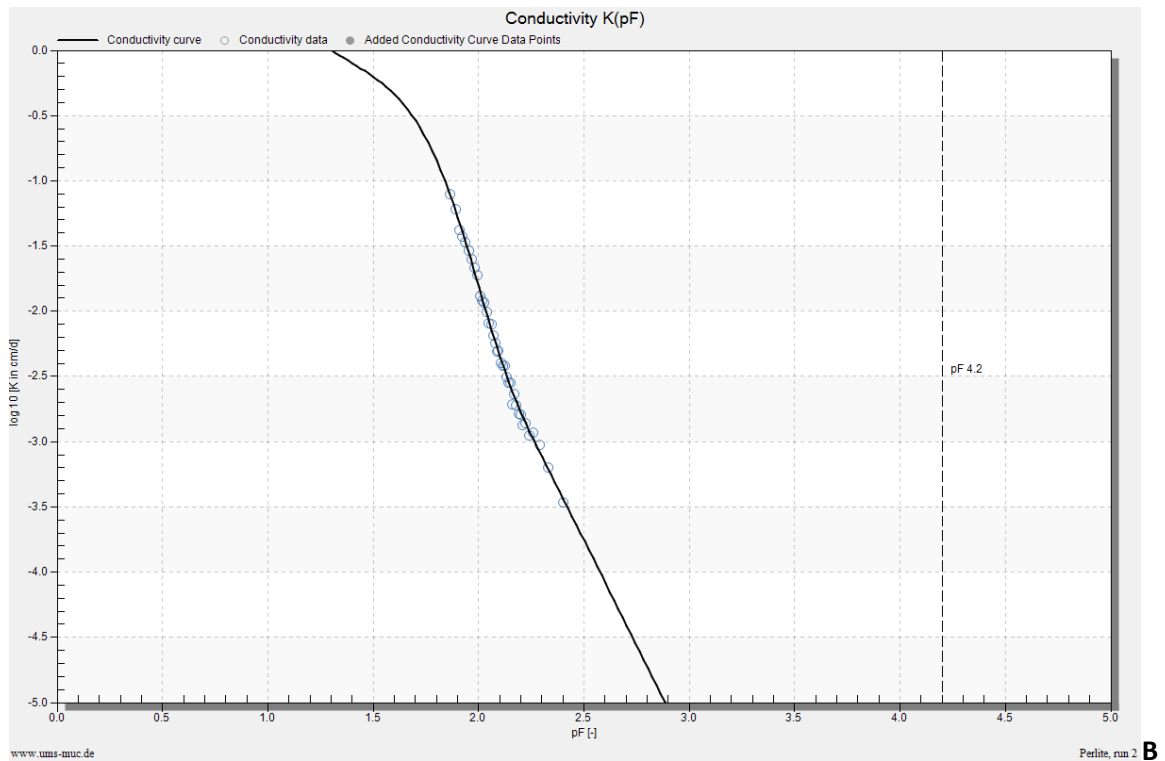
Fig. 1: A) Substrate moisture retention curve (water content vs pF; blue circles are data points directly calculated from the data, black lines indicates curves fitted using van Genuchten's bimodal model, typically used for substrates with non-uniform pore sizes, in this case large pores between the substrate particles and small pores inside the substrate particles); B) "hydraulic conductivity vs pF" and C) "hydraulic conductivity vs VWC" curves (blue circles are data points directly calculated from the data, black lines indicates curves fitted using the Peters- Durner II (2008) equation. Note that hydraulic conductivity is plotted on a log scale (y-axes).

As the pF of the perlite substrate decrease decreases from about 1.8 to 2.5, the hydraulic conductivity decreases by about a factor 1000. This drastic decrease in hydraulic conductivity with a decrease in substrate water content or pF means that water will move much more slowly through the substrate as the substrate dries out. Note that a pF of 1.7 corresponds to a water or matric potential of about -50 kPa. The substrate seems to have little or no available water below a water content of about 15%.

The substrate-specific calibration equation needed to convert the dielectric value, directly measured by the sensor, to substrate water content was obtained using the procedure described by Nemali et al. (2007). Briefly, to obtain a range of water contents in each substrate, from dry to near saturation, different volumes of deionized water were added to perlite samples of about 2L and mixed thoroughly to obtain uniformity. Substrates were then transferred into glass beakers with known volume (1170 mL). Before inserting any probe, the initial weight of the beakers and substrate was determined. Three GS3 probes connected to a CR1000 datalogger (Campbell Scientific, Inc., Logan, UT, USA) were inserted carefully in each beaker so as to not compress the substrate during insertion. After measuring the output from the probes, the substrate in the beakers was dried in a forced-air oven maintained at 105 °C. The substrate was weighed after drying, and used to determine the substrate water content. The volumetric substrate water content was determined by converting grams of water in the substrate to milliliter of water assuming that 1 g of water = 1 mL.

In Fig. 2 is reported the relationship found between volumetric water content of the substrate (VWC) and the dielectric permittivity (ε) measured by the GS3 sensor in perlite.

The resulting equation

$$VWC = -0.0006\, \varepsilon^2 + 0.0331\, \varepsilon - 0.0434$$

was used in the further steps of the study for VWC measurements.
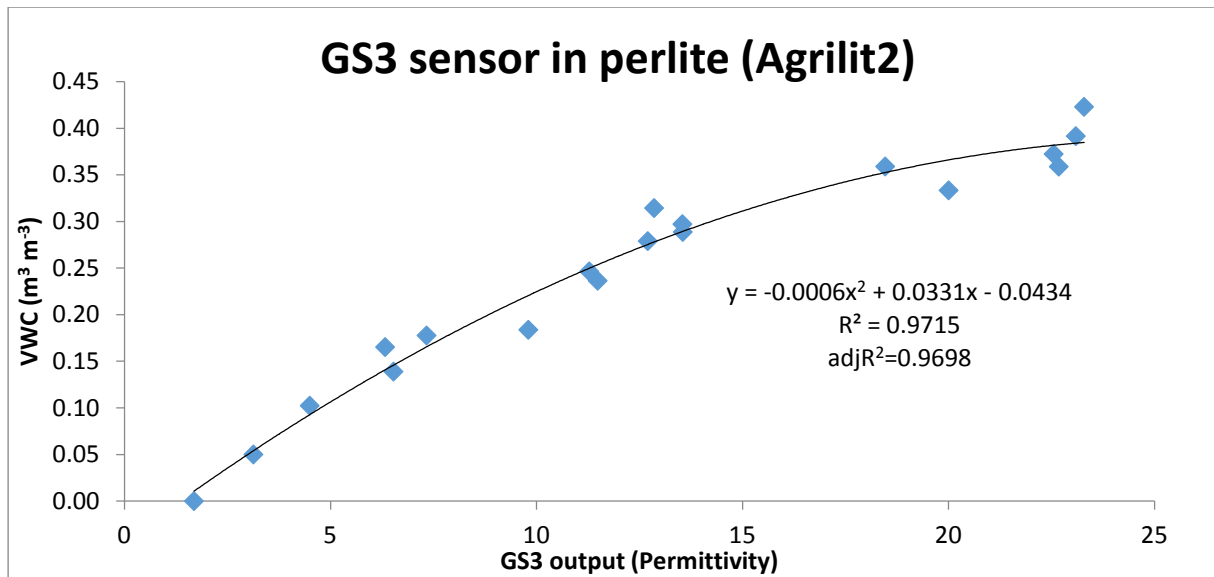
Fig. 2: Relationship between volumetric water content of the substrate (VWC) and the dielectric permittivity (ε) measured by the GS3 sensor in perlite.

OBSERVATIONS ON THE SUBSTRATE ELECTRICAL CONDUCTIVITY MEASUREMENTS USING GS3 SENSORS IN PERLITE

The Hilhorst equation has been proposed as a tool to convert the bulk EC (ECb), measured by the sensor, into the pore EC (ECp).

A test was carried out to verify the ability of the GS3 to measure the substrate EC trend in real conditions of cultivation in a greenhouse soilless tomato cultivation in perlite subjected to variations of the substrate salinity status.

18 plastic pots (volume=10L), containing tomato plants growing on perlite, have been subjected to irrigation for about four weeks with a schedule set in order to have a leaching fraction of about 90%, which enabled the maintenance of very similar EC both in the root-zone and the drainage solutions (Magàn et L., 2008). A low and a high EC nutrient solution (EC = 2.4 and 4.1 dS/m, respectively) were used in the first and the second half of the test, respectively. In each pot, one GS3 sensor was inserted; the sensors were connected to a CR1000 datalogger, programmed to measure and record sensor outputs (dielectric permittivity, bulk EC and temperature) with a scan rate of 15 minutes.

The EC of the drainage fraction from all the 18 experimental units (pots) was measured approximately every two days, and used as a measure of the real substrate ECp (ECp$_{real}$). The ECb was measured directly by the GS3 sensors. The resulting ECp was calculated automatically by the datalogger with the Hilhorst equation (ECp$_{Hilhorst}$) and the data were stored:

$$ECp = ((80.3-0.37*(SoilTemp-20)*ECbulk)/(Dielectric-6.0)$$

The three parameters were recorded over the test in all the 18 experimental units.

The three parameters (ECb, ECp_{real} and $ECp_{Hilhorst}$) were able to describe the increasing trend of salinity in the substrate (Fig. 3). However, both ECb and $ECp_{Hilhorst}$ resulted in different values, in absolute terms, compared to the ECp_{real} provided by the measurement of the leacheate. In particular, the $ECp_{Hilhorst}$ values were always lower than ECp_{real} ones (0.60 vs 2.48 dS/m and 1.10 vs 4.68 dS/m, on average, respectively in the first and second half of the test). However, the $ECp_{Hilhorst}$ was strongly correlated with the real ECp in the substrate (**ECp_{real} = 4.2815 $ECp_{Hilhorst}$ - 0.0766**, R^2=0.99).

According to our results, it seems that GS3 sensors used in perlite are not able to provide ready-to-use values of ECp simply applying the Hilhorst equation, as suggested by the producer. However, the values provided by the sensor are strongly correlated with the real ECp of the substrate, therefore, using a proper second-step equation could help to convert the obtained value into the real ECp of the substrate.
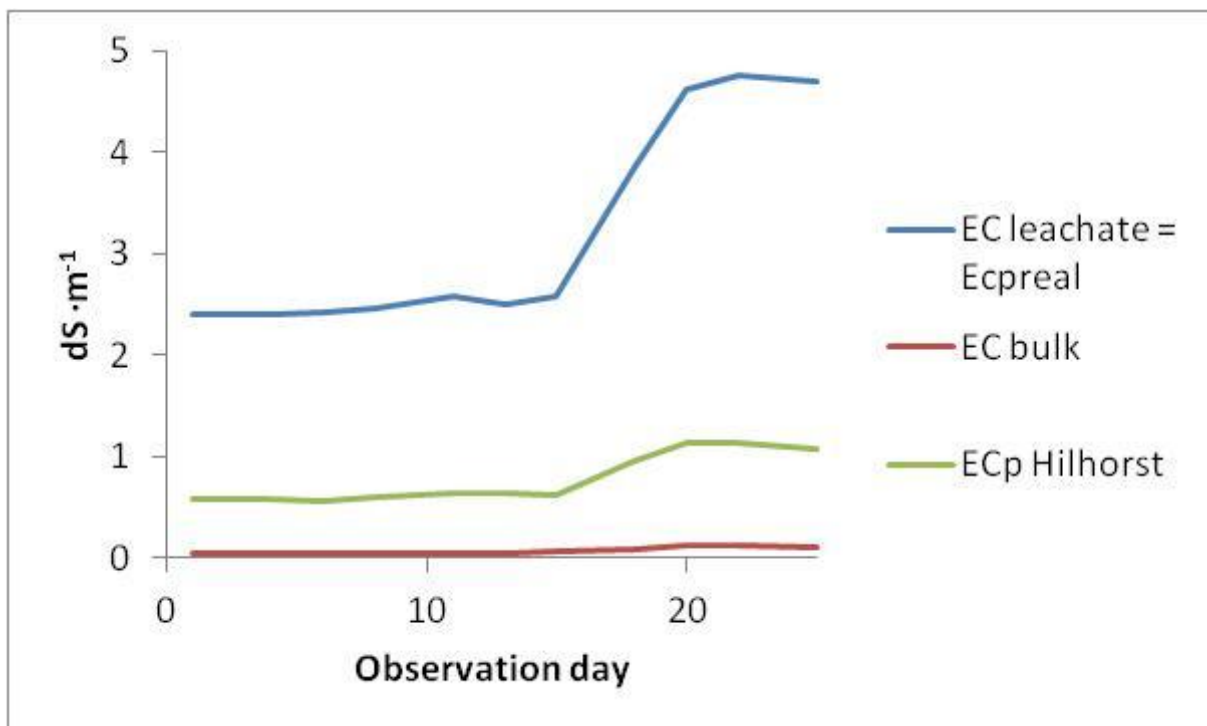
Fig. 3: Trend of electrical conductivity (EC) of leachate, assumed similar to the real pore EC in the root zone (ECpreal) , the bulk EC measured with GS3 sensors and the pore EC calculated with the Hilhorst equation, in perlite substrate with tomato plants irrigated using a fertilizer solution with increasing EC and with a leaching fraction of about 90%.

PHASE 2

Different strategies for the automatic irrigation management were tested in a six-months tomato cultivation trial. The strategies based on the automatic sensor-based scheduling of fertigation were compared with a timer-based approach. In the study, we used a moderate saline water (1 g/L NaCl) for the preparation of the nutrient solution, and we aimed to the rational control of water supply and leaching in order to manage the salinity building-up in the growing media under pre-fixed salinity thresholds.

EXPERIMENT SET-UP

The experiment was carried out in a plastic (polymetacrylate) greenhouse at the Experimental Farm "La Noria" of the Institute of Sciences of Food Production (ISPA-CNR, Picture 1) in Mola di Bari, Southern Italy, during a winter-summer growing cycle (January - July).

Seedlings of tomato [*Solanum lycopersicum* L., 'Creativo' (Clause), cherry type] were transplanted on September 24th 2014 at the second true-leaf stage into 10 L plastic pots (one plant per pot) with bottom holes, filled with 8 L of 1-2 mm grain-size perlite (Agrilit 2, Perlite Italiana, Corsico (MI), Italy). Pots were placed on rows at a density of 3.5 plants/m^2, on plastic troughs (Agridrain, Perlite Italiana, Corsico (MI), Italy) with a container at the end of each through for the runoff collection.

One GS3 sensor (Decagon Devices, Pullman, WA) and one tensiometer (LT1 28 cm, Tensio-Technik, Geisenheim, Germany) were placed in the pot containing the plant placed in the middle of each experimental unit (see below for details on the experimental design) (Picture 2). GS3 sensor measures: i) the dielectric constant of the substrate, which can be converted in VWC using an appropriate calibration equation; in this experiment we used a specific equation arising from a preliminary laboratory test (VWC= -0.0006 ε^2 + 0.0331 ε - 0.0434); ii) substrate bulk EC, which was first converted in pore EC (ECp) using the Hilhorst equation and then corrected according to a second-step equation found during the Phase 1 of the present research (see pag. 21); iii) substrate temperature. We developed an automatic irrigation system intended for experimental purposes, based on a CR1000 Datalogger, a relay driver (SDM16AC/DC controller; Campbell Scientific, Logan, UT) and a set of irrigation solenoid valves. The system was able to collect the soil moisture

Picture 2: Particular of the pot in the experimental unit containing a tensiometer and a GS3 sensor.

sensor measurements, to process the data according to specific programs developed in CR Basic language for each specific experiment, and to activate irrigation automatically (Picture 3).
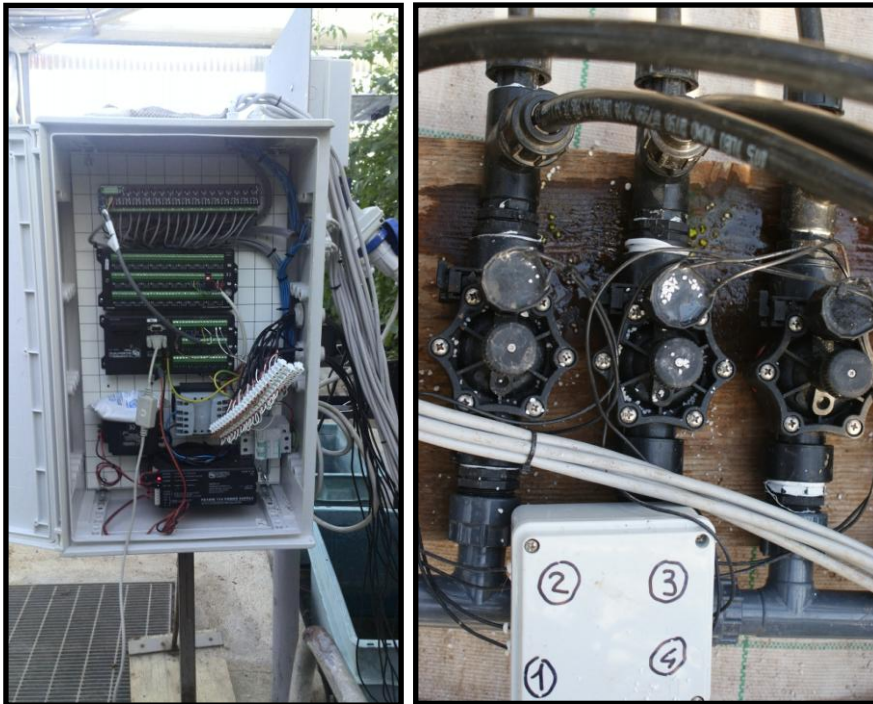
Picture 3: Experimental system for sensor-based irrigation.

From the transplant on, all plants were well watered using a timer-based schedule for approximately 4 weeks, in order to allow the seedlings to establish. This period was also used to perform the Phase 1 of the research, with the objective to verify the ability of the GS3 to measure the substrate EC trend in real conditions of cultivation (greenhouse soilless tomato cultivation in perlite subjected to variations of the substrate salinity status) (see pagg. 20-21). Plants were watered at each irrigation with a nutrient solution (NS) prepared with rain water and containing 153 mg/L N, 311 mg/L K, 50 mg/L P, 145 mg/L Mg, 167 mg/L Ca, 155 mg/L S and micronutrients applied according to Johnson et al. (1957), with EC of 2.3 dS·m^{-1} and pH of 5.5 after correction with KOH. Starting from October 16th 2014, saline conditions were applied by adding 1 g/L NaCl to the NS, leading to a final EC of 4.2 dS/m. Irrigation treatments were applied on November 5th 2014.

The experiment consisted in the following treatments:

- **TIMER**: this represented the lowest level of control, with no control of real water needs of plants and no control of real necessity of leaching. A pre-determined irrigation schedule was set in order to obtain a constant HIGH LEACHING (≈50%), according to the common practice.

- **VWC**: this represented an intermediate level of control. The system used only the VWC sensor measurement to irrigate plants according to a predetermined VWC set-point. Each irrigation event had a duration such as to ensure a HIGH LEACHING (≈50% as target).

-**VWC+EC (5 dS/m)** and **VWC+EC (7 dS/m):** this represented the highest level of control. The system used the VWC sensor measurement to irrigate plants according to a predetermined set-point (the same of treatment VWC). After taking the decision to irrigate, the system decided the duration of the event according to the EC reading and subsequent calculations to convert the ECb in the ECp: if a specific ECp set-point was exceeded, the event had a duration such as to ensure a HIGH LEACHING; if not, the event was a LOW LEACHING(≈25% as target). We used two ECp set points in the two treatments, 5 and 7 dS/m, respectively.

Treatments were arranged in a randomized complete design with three replications. Each trough, containing 11 plants, represented an experimental unit. The first plant at the upper and lower end of each trough was not taken into account for harvesting, sampling and measurements. Two external rows served as guards. A layout of the experiment is reported in Picture 4 and Fig. 4.

Picture 4: Experiment on soilless tomato cultivation using sensor-based irrigation management in saline conditions .
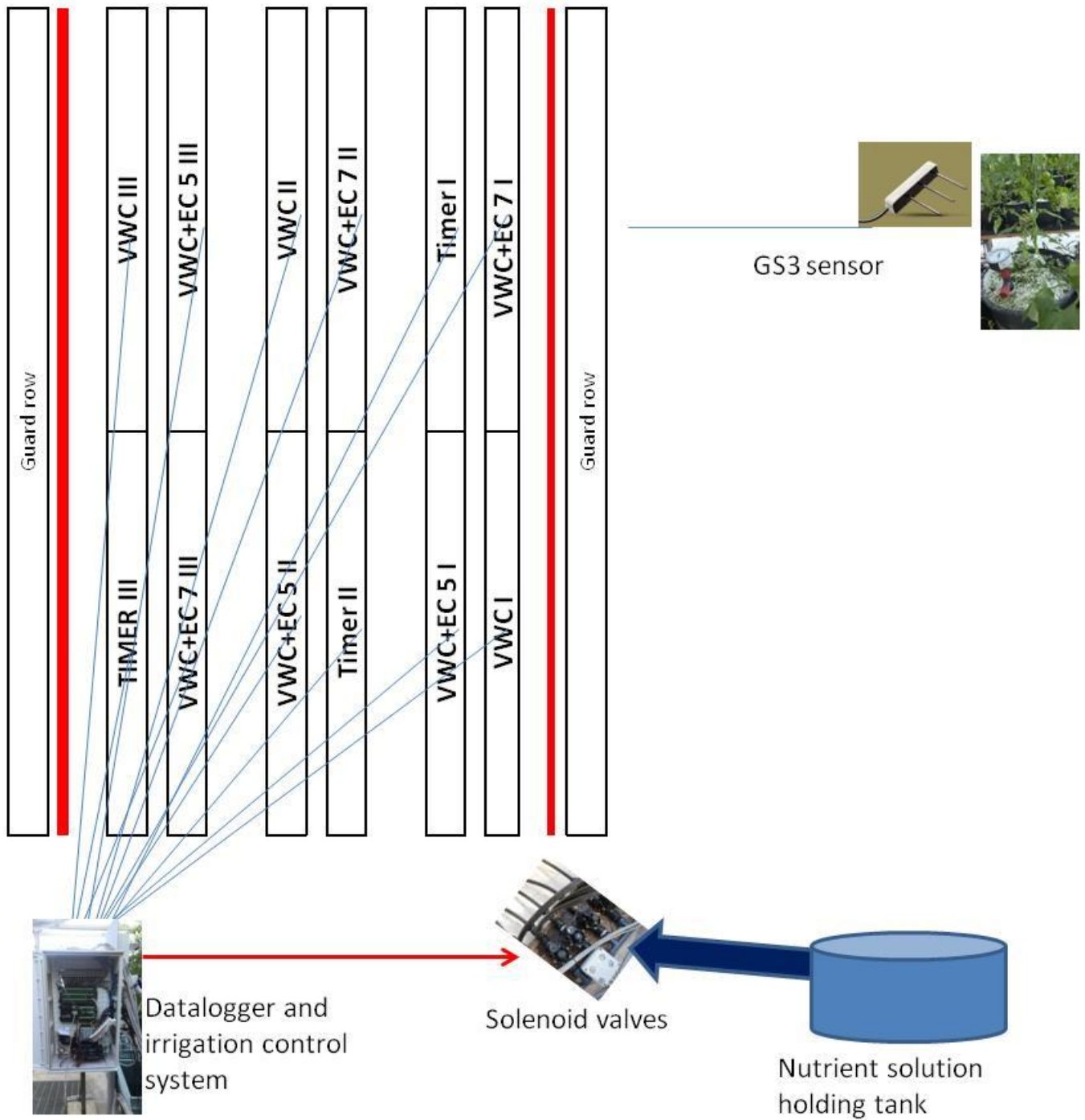
Fig 4: Layout of the experiment.

The experiment was terminated on April 03rd 2015. Plants were trained vertically and topped at 7th cluster. Periodic operations of binding, lateral stem and basal leaf pruning were carried out. Pollination was guaranteed by introducing an hive of bumblebees (Bombus terrestris L.) into the

greenhouse beginning from the anthesis of the first cluster. Climatic parameters inside the greenhouse during the trial are reported in Fig. 5.
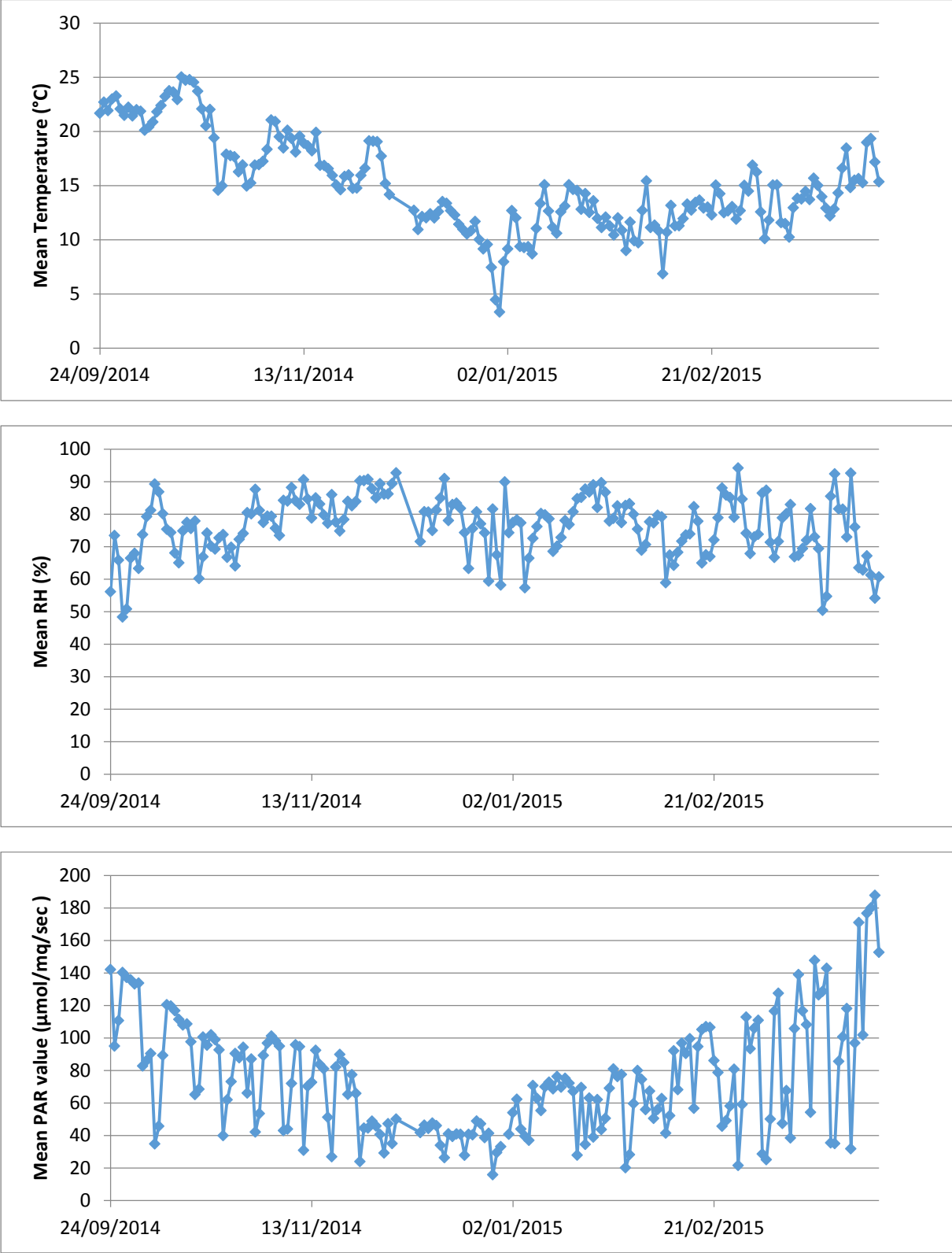
Fig 5: Mean daily air temperature, relative humidity (RH) and PAR value inside the greenhouse during the experiment.

A specific program was compiled and uploaded into the CR1000 unit in order to collect and process data and automate irrigation consequently. The program was compiled in CR Basic language using a LoggerNet 3.1 software (Campbell Scientific, Logan, UT).

The logic of the program is simple: if the measured VWC is below the VWC set-point for a particular plot (the VWC setpoint was the same for all the plots in this experiment), the plot needs to be irrigated. For plots of 'VWC' treatment, in which we simulated the availability of only VWC measurements, each irrigation event will had a duration such as to ensure a HIGH LEACHING.

For plots of 'VWC+EC' treatments, after taking the decision to irrigate, the decided the duration of the event according to the EC reading: if a specific EC set-point is exceeded, the event will have a duration such as to ensure a HIGH LEACHING; if not, the event will be a LOW LEACHING. Two specific EC thresholds (5 and 7 dS/m) have been tested in the experiment.

The basic logic of the program is described in the diagram reported in Fig. 6.

Fig 6: Scheme of the data acquisition and processing alogorithm in the program used for the automatic irrigation system.

An example of the program used in the experiment is reported below (the part of the program related to the irrigation activation in the 'TIMER' treatment has been deleted for clarity, being this a simple pre-fixed schedule):

***

'Program name: GS3 PROGRAM For IRRIGATION AND LEACHING CONTROL (IRMA PROJECT: TOMATO AND SALINITY TRIAL).CR1
'Date written: 08/September/2014
'Created by Francesco F. Montesano and Angelo Parente (CNR – ISPA, Italy); a special thank to Marc van Iersel (University of Georgia, USA) for his suggestions and support
'{CR1000}
' Program for irrigation and leaching percentage determination based on VWC and EC measured using Decagon GS3 sensors,
' one CR1000 datalogger, one AM16/32AC relay drivers
' and one 24VAC transformer to power 9 solenoids valves
'**;
' Flag usage
' Flag 1: used to assure that set point part of the program is executed only the very first time the program runs.
' Flag 2: used to trigger irrigation.
'**

' CR1000 Control port usage:
' C1: Port 1 on 1 relay driver (address 0)
' C2: Port 2 on 1 relay driver (address 0)
' C3: Port 3 on 1 relay driver (address 0)
' C4:
' C5:
' C6:
' C7: Used to measure 12 GS-3 sensors, one wire to all GS3 sensors
' C8:
'**;
' Switched 12 V: connected to white wire of all GS3 sensors (provides power to sensors)
' CHECK THIS WIRING WITH THE ACTUAL GS3 WIRING
'**;
' SDM16AC/DC relay driver wiring
' There is one relay driver with address 0.
' C1 on relay driver to C1 on CR1000
' C2 on relay driver to C2 on CR1000;
' C3 on relay driver to C3 on CR1000;
' 12V on relay driver to 12 V on CR1000
' Ground on relay driver to ground on CR1000
'**;
' GS3 wiring:
'All white wires chained together, one wire To SW12V
'All red wires chained together, one wire to C7
'all ground wires chained together, one wire to Ground
'ALL GS3 SENSORS HAVE BEEN GIVEN UNIQUE SDI-12 ADDRESSES (1-6; A-C; G-I);
'AND SENSORS ARE LABELED WITH THEIR ADDRESS
'**;

' *Wiring of 24VAC wiring to supply power to solenoids*
' *24VAC power transformer is connected to 220 V power cable and plug*
' *This provides 24 VAC for solenoids*
' *One of the two 24 VAC terminals is connected to all 'COM' channels on the relay driver*
' *The other of the two 24 VAC terminals is connected directly to all solenoid valves (red wires, chained together)*
' *The other wire for the solenoid valves is connected to the 'NO' (normally open) channels on the relay drivers.*

'***;
'*Treatments identifications with related plot number in the program and address of GS3 sensor used in the plot:*
'*VWC I = Plot n. 1;   GS3 # 1;*
'*VWC II = Plot n. 2;   GS3 # 2;*
'*VWC III = Plot n. 3;   GS3 # 3;*

'*VWC+EC 5 I = Plot n. 4;   GS3 # 4;*
'*VWC+EC 5 II = Plot n. 5;   GS3 # 5;*
'*VWC+EC 5 III = Plot n. 6;   GS3 # 6;*

'*VWC+EC 7 I = Plot n. 7;   GS3 # A;*
'*VWC+EC 7 II = Plot n. 8;   GS3 # B;*
'*VWC+EC 7 III = Plot n. 9;   GS3 # C;*

'*Timer I = Plot n. 10;   GS3 # G;*
'*Timer II = Plot n. 11;   GS3 # H;*
'*Timer III = Plot n. 12;   GS3 # I;*

' *Program runs every 20 minutes. You can change this scan-rate value*

'\\\\\\\\\\\\\\\\\\\\\\\\\\\ *DECLARATIONS* ///////////////////////////

'Const 12 = 12
'*Declare array of flags*
Public Flag(8) As Boolean

Public P(12,3)
Dim i, j
Public HLduration
Public LLduration

Public Dielectric(12)

Public VWC(12)
Public VWCavgTRT_VWC
Public VWCavgTRT_VWC_EC5
Public VWCavgTRT_VWC_EC7
Public VWCavgTRT_Timer

Public ECbulk(12)
Public ECBavgTRT_VWC

```
Public ECBavgTRT_VWC_EC5
Public ECBavgTRT_VWC_EC7
Public ECBavgTRT_VWC_Timer

Public ECpore(12)
Public ECPavgTRT_VWC
Public ECPavgTRT_VWC_EC5
Public ECPavgTRT_VWC_EC7
Public ECPavgTRT_Timer

Public SoilTemp(12)
Public VWCset(9)
Public ECset(9)
Public LowLeaching(9)
Public HighLeaching(9)
Public IRRinstruction (16)
Public Time
Public LowLCount(16)
Public HighLCount(16)

Public Irrigate

Units VWC() = m3/m3
Units ECbulk() = dS/m
Units ECpore() = dS/m
Units SoilTemp() = deg_C


'\\\\\\\\\\\\\\\\\\\\\\\\\ OUTPUT SECTION ///////////////////////

DataTable(GS3Out,1,-1)
 'change the dataInterval to reflect how often you would like points to be logged.
 DataInterval (0,20,Min,0)
 Sample(12,Dielectric(),FP2)
 Sample(12,VWC(),FP2)
 Sample(12,ECbulk(),FP2)
 Sample(12,ECpore(),FP2)
 Sample (12,SoilTemp(),FP2)
 Sample(12,LowLCount(),FP2)
 Sample(12,HighLCount(),FP2)
EndTable

DataTable (GS3Out_AVG_TRT, 1, -1)
 DataInterval (0,20,Min,0)
Sample (1,VWCavgTRT_VWC, FP2)
Sample (1,VWCavgTRT_VWC_EC5, FP2)
Sample (1,VWCavgTRT_VWC_EC7, FP2)
Sample (1,VWCavgTRT_Timer, FP2)
Sample (1,ECBavgTRT_VWC, FP2)
Sample (1,ECBavgTRT_VWC_EC5, FP2)
Sample (1,ECBavgTRT_VWC_EC7, FP2)
```

```
Sample (1,ECBavgTRT_VWC_Timer, FP2)
Sample (1,ECPavgTRT_VWC, FP2)
Sample (1,ECPavgTRT_VWC_EC5, FP2)
Sample (1,ECPavgTRT_VWC_EC7, FP2)
Sample (1,ECPavgTRT_Timer, FP2)
EndTable

DataTable (GS3outAVG,True,-1)
DataInterval (0,120,Min,10)
Average (12,Dielectric(),FP2,False)
Average(12,VWC(),FP2,False)
Average(12,ECbulk(),FP2, False)
Average(12,ECpore(),FP2, False)
Average (12,SoilTemp(),FP2, False)
EndTable

DataTable(CumulativeIrr,1,-1)
  DataInterval(1440,1440,Min,0)
  Sample(16, LowLCount, FP2)
  Sample(16, HighLCount, FP2)
EndTable

'\\\\\\\\\\\\\\\\\\\\\\\\\\\\ PROGRAM //////////////////////////

BeginProg
  Scan(1200,Sec, 0, 0)
    '******************************************************************;
    ' The first time the program runs, all set points will be set.       ;
    ' This program will be skipped in future program executions, because  ;
    ' Flag 1 will be set high later on.                      ;
    '******************************************************************;
'Set time duration (in minutes) for High Leaching (HL) and Low Leaching (LL) irrigation events.
'Important: the minute value needs to be +1 than the desired duration (i.e. write 13 if you want a 12
'minutes irrigation)
HLduration = xx
LLduration = xx
For i = 1 to 9
LowLeaching(i) = 0
HighLeaching(i) = 0
IRRinstruction(i) = 0
next i

'Only channels 1-9 of the SDM16AC/DC relay driver are used in the experiment, so channels 10-16 are
'set permanently off by setting IRRinstruction(10-16) = 0

IRRinstruction(10)=0
IRRinstruction(11)=0
IRRinstruction(12)=0
IRRinstruction(13)=0
IRRinstruction(14)=0
IRRinstruction(15)=0
```

```
IRRinstruction(16)=0

  If  Flag(1) = False Then
     'Introduce the setpoints for VWC and EC. EC setpoints values are calculated on the base of a
  'relationship found between ECp by Hilorst equation and ECp empirically measured in the substrate in
  'the conditions of the experiment. An ECp Hilorst of 1.182 corresponds to an ECp in the substrate of 5
  'dS/m; An ECp Hilorst of 1.644 corresponds to an ECp in the substrate of 7 dS/m;

     VWCset(1) = 0.30
     'ECset(1) = 0
     VWCset(2) = 0.30
     'ECset(2) = 0
     VWCset(3) = 0.30
     'ECset(3) = 0
     VWCset(4) = 0.30
     ECset(4) = 1.182
     VWCset(5) = 0.30
     ECset(5) = 1.182
     VWCset(6) = 0.30
     ECset(6) = 1.182
     VWCset(7) = 0.30
     ECset(7) = 1.644
     VWCset(8) = 0.30
     ECset(8) = 1.644
     VWCset(9) = 0.30
     ECset(9) = 1.644


     ' After setting all the set points; set flag 1 high to assure that this part of the program will be
  'skipped in future
     Flag(1) = true
  EndIf

     'NOTE: GOT THESE INSTRUCTIONS FROM Example SDI12 Program_GS3.CR1on Decagon website

  SequentialMode
  'excite the sensors through SW-12 port
  SW12(1)

  'Wait one second
  Delay (0,1,Sec)

  'Sequentially measure each sensor named 1- 6, A, B, C, G, H, I on C7.  Returns all 3 values for each
  'sensor.
  SDI12Recorder (P(1,1),7,1,"M!",1.0,0)  'Plot 1
  SDI12Recorder (P(2,1),7,2,"M!",1.0,0)  'Plot 2
  SDI12Recorder (P(3,1),7,3,"M!",1.0,0)  'Plot 3
  SDI12Recorder (P(4,1),7,4,"M!",1.0,0)  'Plot 4
  SDI12Recorder (P(5,1),7,5,"M!",1.0,0)  'Plot 5
  SDI12Recorder (P(6,1),7,6,"M!",1.0,0)  'Plot 6
  SDI12Recorder (P(7,1),7,"A","M!",1.0,0)  'Plot 7
  SDI12Recorder (P(8,1),7,"B","M!",1.0,0)  'Plot 8
```

```
SDI12Recorder (P(9,1),7,"C","M!",1.0,0)  'Plot 9
SDI12Recorder (P(10,1),7,"G","M!",1.0,0)  'Plot 10
SDI12Recorder (P(11,1),7,"H","M!",1.0,0)  'Plot 11
SDI12Recorder (P(12,1),7,"I","M!",1.0,0)  'Plot 12

'Excitation off
SW12(0)

For i = 1 To 12
  'Take bulk dielectric reading from the first element of each sensor array P(i,1) and apply the
'calibration.
  Dielectric(i) = P(i,1)
  'Apply custom calibration for GS3 sensors in Agrilit2
  VWC(i) = -0.0006 * Dielectric(i)^2 + 0.0331 * Dielectric(i) - 0.0434

  'extract the EC and soil temperature from the raw data array.
  SoilTemp(i) = P(i,2)
  ECbulk(i) = P(i,3)/1000
  ' Pore water EC calculated based on Hilhorst equation
  ECpore(i) = ((80.3-0.37*(SoilTemp(i)-20))*ECbulk(i))/(Dielectric(i)-6.0)
Next i

' All 12 GS3 sensors have now been measured
'now calculate the average values for treatment (average of the three replicates), that will be used
'to trigger on irrigation and decide the leaching for the treatment

VWCavgTRT_VWC = ((VWC(1)+VWC(2)+VWC(3))/3)
VWCavgTRT_VWC_EC5 = ((VWC(4)+VWC(5)+VWC(6))/3)
VWCavgTRT_VWC_EC7 = ((VWC(7)+VWC(8)+VWC(9))/3)
VWCavgTRT_Timer = ((VWC(10)+VWC(11)+VWC(12))/3)

ECBavgTRT_VWC = ((ECbulk(1)+ECbulk(2)+ECbulk(3))/3)
ECBavgTRT_VWC_EC5 = ((ECbulk(4)+ECbulk(5)+ECbulk(6))/3)
ECBavgTRT_VWC_EC7 = ((ECbulk(7)+ECbulk(8)+ECbulk(9))/3)
ECBavgTRT_VWC_Timer = ((ECbulk(10)+ECbulk(11)+ECbulk(12))/3)

ECPavgTRT_VWC = ((ECpore(1)+ECpore(2)+ECpore(3))/3)
ECPavgTRT_VWC_EC5 = ((ECpore(4)+ECpore(5)+ECpore(6))/3)
ECPavgTRT_VWC_EC7 = ((ECpore(7)+ECpore(8)+ECpore(9))/3)
ECPavgTRT_Timer = ((ECpore(10)+ECpore(11)+ECpore(12))/3)

'******************************************************************************
  ' Start of the irrigation/fertigation control section (applied to plot 1-9; plots 10-11-12 are controlled
'by a timer).
  'The logic is simple: if the measured VWC is below the VWC set-point for a particular plot (the VWC
'setpoint is the same for all the plots in this experiment), the plot needs to be irrigated. For plants of
'plots 1-3, each irrigation event will have a duration such as to ensure a HIGH LEACHING.
  'For plants of plots 4-9, after taking the decision to irrigate, the system will decide the duration of
'the event according to the EC reading:
  'if a specific EC set-point is exceeded, the event will have a duration such as to ensure a HIGH
LEACHING; if not, the event will be a LOW LEACHING.
```

```
'2 specific EC thresholds  are  tested.

'*****************************************************************************
' +++++++++++++++++++ NEED A Loop HERE +++++++++++++++++++++++++++++++++++++++++
For j = 1 To 3
  'Step 1: determine if the VWC is below the setpoint; in plots 1-3, if irrigation is needed,
'HighLeaching variable is set to 1
  If (VWCavgTRT_VWC < VWCset(j)) Then
  HighLeaching(j) = 1
  ' Count how often the plot is fertigated
  HighLCount(j) = HighLCount(j) + 1
  else
  HighLeaching(j) = 0
  HighLCount(j) = HighLCount(j) + 0
  EndIf
  next j

  For j = 4 to 6
  If (VWCavgTRT_VWC_EC5 < VWCset(j)) Then
  If (ECPavgTRT_VWC_EC5 < ECset(j)) Then
  LowLeaching(j) = 1
  LowLCount(j) = LowLCount(j) + 1

  Else
  HighLeaching(j) = 1
  HighLCount(j) = HighLCount(j) + 1

  EndIf
  Endif
  next j

  For j = 7 to 9
  If (VWCavgTRT_VWC_EC7 < VWCset(j)) Then
  If (ECPavgTRT_VWC_EC7 < ECset(j)) Then
  LowLeaching(j) = 1
  LowLCount(j) = LowLCount(j) + 1
  HighLeaching(j)= 0
  Else
  HighLeaching(j) = 1
  HighLCount(j) = HighLCount(j) + 1
  LowLeaching(j) = 0
  EndIf
  Endif
  next j

' +++++++++++++++++++++++++++++++ end of Loop +++++++++++++++++++++++++++++++++++++

  ' Flag 2 is set high to make sure that that the irrigation is not potentially turned on every time the
'program runs
  ' See Table 2 below for more details.
```

```
    Irrigate = 0

    ' We now have determined which plots need to be irrigated, and for plot 4-9 which ones need a
'High or a Low Leaching;
    ' But note: we have not turned on the irrigation.  This happens later.

    SubScan (60,Sec,19)

       'This will run the following instructions every 60 sec for 19 times, (19  minutes total) at which
'point 'it will stop and go to the next scan
       ' Only turn the irrigation to selected plots on if Flag 2 is low Note: Flag 2 is set high at the end of
'Table 1 above. Thus, the instructions below will be skipped immediately after table 1 is executed.
       ' This is important because the program takes several seconds to run.  If we run irrigation
       ' immediately afterwards, the irrigation will stay on until Table 2 is run again and
       ' turns the irrigation off.  Irrigation would run for less than 10 s.
       ' By skipping this section once immediately following Table 1, this problem is avoided

    If Irrigate = 1 Then
    Time = Time + 1
    For i = 1 to 9
      If LowLeaching(i) = 1 or HighLeaching(i) = 1  Then

      IRRinstruction(i) = 1
      Else
      IRRinstruction(i) = 0
      Endif
         If LowLeaching(i)=1 and Time = LLduration then
         IRRinstruction(i) = 0
         LowLeaching(i)=0
         Endif

         If HighLeaching(i)=1 and Time = HLduration then
         IRRinstruction(i) = 0
         HighLeaching(i)=0
         EndIf
      Next i

    If time = 18 then time = 0

  SDMCD16AC (IRRinstruction(),1,0)

    EndIf

    Irrigate = 1

    ' Set Irrigate to 1  Note that it was set to 0 before the start of the SubScan, causing the above
    ' part of the SubScan to be skipped immediately following the main Scan.  But the second and
'subsequent times the SubScan runs the above instructions will be executed.

    Next SubScan
    ' Now collect output, once a day, 10 minutes before midnight
```

```
        CallTable CumulativeIrr
        CallTable GS3Out
        CallTable GS3outAVG
        CallTable GS3Out_AVG_TRT
    NextScan
EndProg
```

<center>***</center>

Measurements and observations

- <u>VWC and EC trend</u>: during the experiment, the system logged the substrate VWC and EC measured by the sensors every 20 minutes. Every two days, we also measured the EC and the volume of the NS leached out from containers. During the whole experiment duration, approximately once every 10 days a sample of the leachate was collected for each of the experimental units (replications), and a chemical analysis of principal cations and anions was performed using ion chromatography (Dionex DX120, Dionex Corporation, CA, USA), in order to verify the accumulation of salts in the leachate.

- <u>Water consumption</u>: we measured the total NS supplied in the different treatments and the total NS lost as leaching.

- <u>Crop performance</u>: we evaluated the crop performance in terms of yield, fruit quality and water use efficiency (WUE). Each harvest was carried out by picking the entire fruit cluster of a specific order when it had 80% red-ripened fruits on at least 80% of the plants at the experimental unit. At harvests, fruit fresh weight (marketable and unmarketable), fruit number, fruit dry matter and total soluble solids (TSS) were determined. Fruits were divided into three size classes (diameter 20-30 mm, 30–35 mm, >35 mm). Fruits with cracks on the epicarp or with blossom end rot (not marketable) were discarded. WUE was calculated as the ratio of total fresh weight of fruits to the total volume of NS consumed by the system. Fruit quality was assessed in terms of total soluble solids (TSS) content and dry matter content.

- <u>Plant physiological parameters</u>: From December 19th to 24th 2014, measurements were taken on several physiological parameters of plants. Leaf gas exchange parameters (net CO_2 assimilation - A, transpiration - E, stomatal conductance - gs), were measured with a portable photosynthetic open-system ADC-LCA3 (Analytical Development Co., Hoddesdon, UK) equipped with an assimilation leaf chamber 6.2 cm^2 large. Leaf gas-exchange measurements were performed in clear sky conditions (PAR ≈ 260 µmol m^{-2} s^{-1}) between 11:30 and 12:30. On two plants per plot, two upper fully-expanded, healthy, terminal, and sun well-exposed leaves were chosen for measurements.

Chlorophyll fluorescence was measured through measurements of the Chl fluorecence imaging using a blue version of the mini cholophyll fluorometer IMAG (Walz, Effeltrich, Germany). Pixel value images of the fluorescence parameters were displayed with the help of a false colour code ranging from black (0.00) through red, yellow, green, blue to pink (ending at 1.00). Chl a fluorescence

parameters were assessed by the saturation pulse method in the most recently expanded leaf of three plants from each treatment. Leaves were dark-adapted for 15 min., and then images of basal fluorescence (F0) were obtained by applying measuring light pulses modulated at 1 Hz, while images of the maximal fluorescence yield (Fm) were obtained with the help of saturating blue pulse at 10 Hz. Relative water content (RWC) and membrane stability index (MSI) were determined on leaf samples. RWC was determined according to Turner (1981). MSI was estimated according to Rady (2011) by taking 200 mg leaf material, in two sets, in test tubes containing 10 cm^3 of double distilled water. One set was heated at 40 °C for 30 min in a water bath, and the electrical conductivity of the solution was recorded on conductivity bridge (C1). Second set was boiled as 100 °C on a boiling water bath for 10 min, and conductivity was measured on conductivity bridge (C2). MSI was calculated by the formula: MSI % = [1 − (C1/C2)] × 100.

Plant water status was assessed by measuring noon water potential on covered leaf using a pressure chamber Scholander-Hammel type (Scholander et al., 1965). The measurement was replicated on six plants per treatment (two plants per replication unit).

Concentrations of principal anions and cations were determined on leaf tissue samples and on fruits from 3rd and 6th cluster by ionic chromatography with conductivity detector using an IonPack CG12A pre-column and IonPack CS12A separation column (Di Gioia et al., 2013).

RESULTS

The system was able to automate irrigation according to the variations of VWC and EC in the growing substrate. In Fig. 7 is reported the trend of the moisture in the substrates subjected to sensor-based irrigation. The system was able to automate irrigation according to the desired VWC set-point, and moisture never dropped below the set-point (0.3 m^3 m^{-3}). Only for the treatment VWC+EC(7 dS/m) we observed higher fluctuations of the sensor readings in the final part of the experiment, probably as a result of the salinity build-up in the substrate which may have led to a lower measurement accuracy. However, also in this case the range of measurement fluctuations remained limited to a few percent.
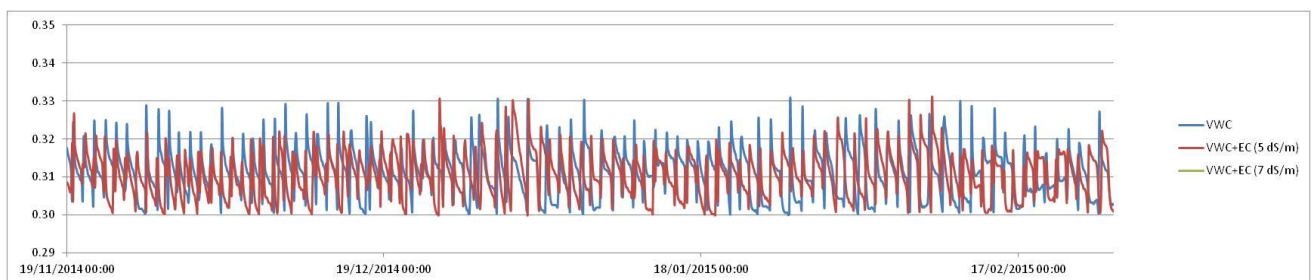

Fig 7: Variation of VWC in the substrates subjected to sensor-based irrigation in a selected period of the experiment.

In Fig 8 (a-d) is reported the trend of the ECp measured in the substrate and in the leachate. Values of ECp are calculated applying to the ECb measured by the sensors the Hilorst equation and then the "second step" equation empirically determined during the phase 1 of the experiment. In 'VWC' and 'Timer' treatment, the system did not take into account the substrate EC measurement for the irrigation management, which was based on pre-fixed schedule in the case of 'Timer' and on the only VWC variations in the 'VWC' treatment. In those two treatments, a high leaching was provided at each irrigation event, resulting in a substrate EC pretty stable over time and showing values close to the EC of the NS (Fig 8 a and b).

In treatments 'VWC+EC(5 dS/m)' and 'VWC+EC(7 dS/m)', the system automatically decided when to irrigate on the basis of the VWC fluctuations, and how much NS supply according to the EC measured in the substrate, choosing between a LOW Leaching or a HIGH Leaching irrigation with the aim to maintain the substrate EC below the pre-fixed set point (5 and 7 dS/m, respectively), as shown in Fig 8 c and d.
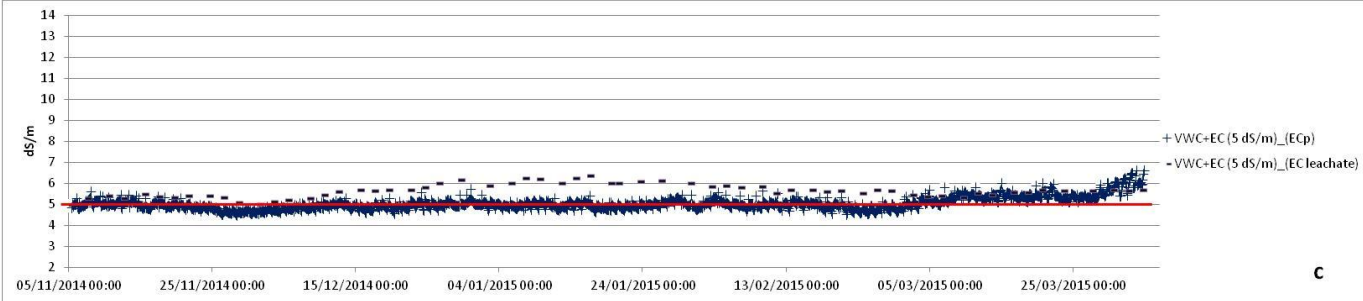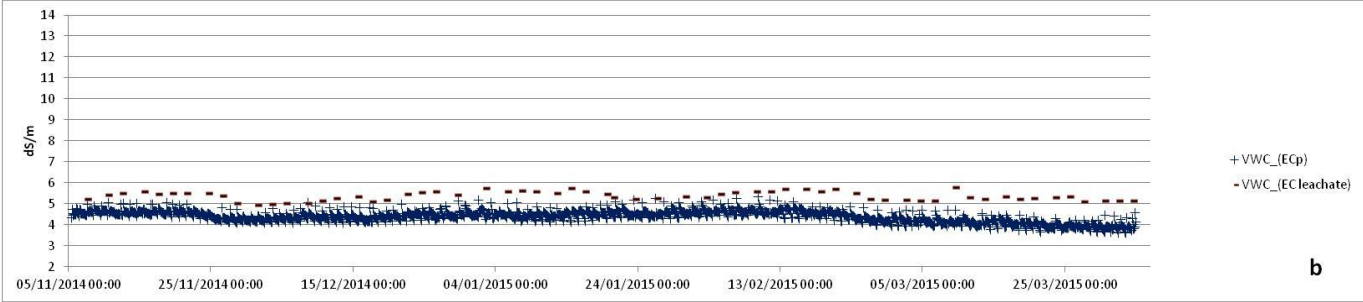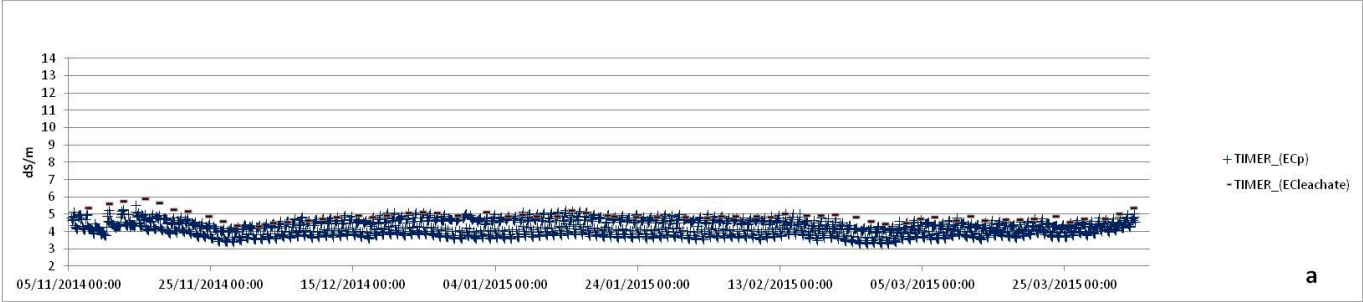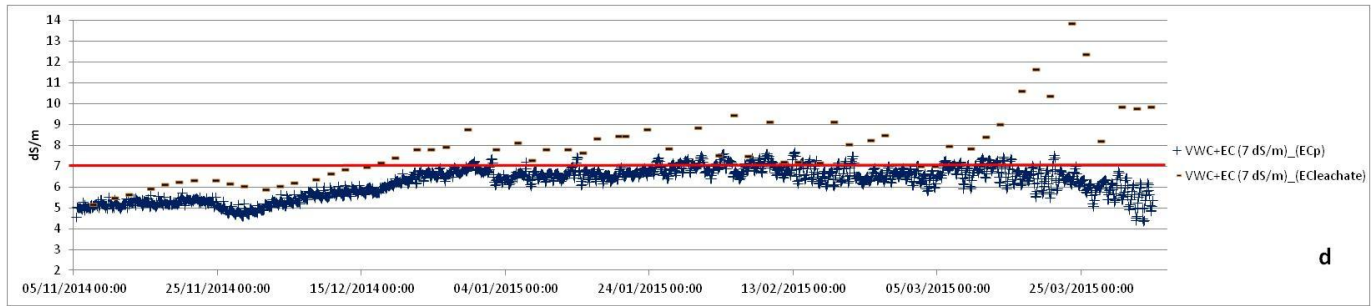
Fig. 8: Trend of the EC measured in the substrate by the GS3 sensors and in the leachate.

The chemical composition analysis on the leachate confirmed the higher accumulation of Na in the substrate, and then in the leachate, in the 'VWC+EC(7 dS/m)' treatment, as a result of the higher EC set-point fixed. Lower differences among treatments were observed for the concentration of other mineral elements (macronutrients) in the leachate, confirming the role of toxic elements (i.e. Na) accumulation in the root-zone salinity imbalance.

Total water consumption (the total water supplied to the crop) was reduced progressively with the increasing level of control of substrate parameters. The highest water consumption was registered in 'Timer', followed by 'VWC', 'VWC+EC(5 dS/m)' and 'VWC+EC(7 dS/m)' treatments; the same trend was observed for the leaching fraction value. As expected, a first contribution to water saving was due to the control of VWC, allowing to supply water through irrigation only when moisture decreased below the prefixed set-point. A further contribution for a more efficient irrigation administration was due to the control of substrate EC in 'VWC+EC(5 dS/m)' and 'VWC+EC(7 dS/m)' treatments, which allowed to increase the leaching fraction only when needed to restore the substrate EC below the predetermined set-point (the higher the EC set-point value, the lower the water used to leach out excessive salts in the substrate).

The total and marketable yield was not different for 'Timer', 'VWC' and 'VWC+EC(5 dS/m)' treatments, while was slightly reduced (less than 10%) in 'VWC+EC(7 dS/m)' treatment. Fruits from all treatments showed a high qualitative profile, with a slight increase in terms of TSS and fruits belonging to the 20-30 mm diameter class in the 'VWC+EC(7 dS/m)' treatment, in particular in fruit clusters harvested in the last part of the growing cycle. The results confirm the possibility to obtain similar crop performances (in terms of yield and quality) with a fraction of the water consumption, by irrigation management based on real-time control of root-zone conditions. It is also confirmed that tomato yield may be reduced by increasing root-zone salinity.

A fundamental management consideration for soil-less growing systems is the requirement to maintain the salinity of the root zone solution at levels which are not detrimental to optimal crop production (Sonneveld, 2000).

Threshold salinity values reported in literature range from 2.5–3 dS/m (Sonneveld and Welles, 1988; Sonneveld and van der Burg, 1991; Megàn et al., 2008), to values of 5–6 dS/m (Adams, 1989; Gough and Hobson, 1990; Willumsen et al., 1996). Our results show that an increase of the substrate EC set-point from 5 to 7 dS/m may imply a certain reduction of the yield performance. However, sensor-based irrigation with the control of the substrate EC may also be considered a feasible tool to improve fruit quality by applying controlled salt stress.

Under a physiological point of view, the salt stress resulted in a lower leaf water potential value in 'VWC+EC(7 dS/m)' treatment, but, in general, no severe damages were observed in terms of other measured physiological parameters, confirming the general good adaptation of tomato crop to moderate salt stress conditions.

Conclusions

Efforts to optimize water use in Mediterranean greenhouse industry may involve improvements in irrigation management and, when possible, use of water with moderate levels of salinity.

Sensors for measuring water status and salinity in the root zone are a dynamic and constantly developing area of technology for both technical and commercial reasons. Our study proves that substrate-sensor networks could be used for irrigation and leaching control in soilless tomato production in moderate saline conditions. Compared to timer-based approach, sensor-based irrigation could enable the effective real-time estimation of crop water needs on the base of the water availability in the substrate. Moreover, continuous control of salinity status in the root-zone may help to reduce leaching and prevent excessive salt accumulation detrimental for the crop performance.

Under a technical point of view, while real-time VWC measurement could be considered nowadays reliable and easy to be used for irrigation management purpose, substrate EC measurement by sensors is still problematic with sensors now available on market, and requires higher attention for the interpretation and the use of data aimed to automatic irrigation decision.

In this study, using sensor-based approach we were able to obtain the same crop performance of a traditional timer-based approach, but with a substantial water saving due to the rational control of leaching as a tool to prevent excess salinity in the substrate. We also proved the importance to select appropriate EC set-points in order to prevent detrimental effects on the crop performance.

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