Sensor-based management of container nursery crops irrigated with fresh or saline water

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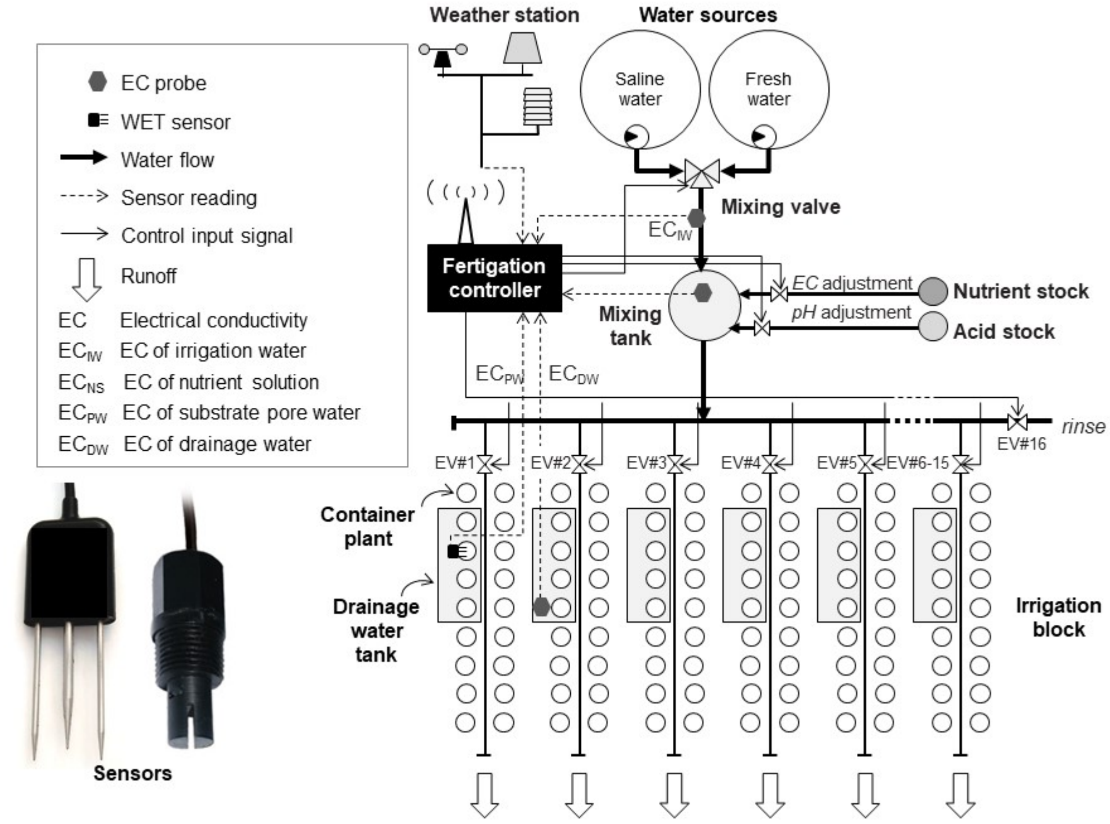
Highlights

- A controller was designed to irrigate container crops with fresh or saline water.
- Substrate salinization was prevented using different sensors and control strategies.
- The prototype reduced fresh water use by 17% to 84% compared to standard system.
- The prototype also decreased the loss of nitrogen and phosphorus by 53% to 84%.

Graphical abstract



Container hardy ornamental nursery stocks are generally grown with considerable applications of water and agrochemicals, resulting in an important pollution. These crops are often over-irrigated because of inaccurate scheduling, which is generally based on growers' experience. The design of an efficient irrigation management system is therefore crucial to improve profitability and sustainability of production. Reclaimed municipal or industrial wastewater is a source of irrigation water alternative to fresh water; generally, reclaimed wastewater has a high salt content and its use can induce salinity stress in sensitive crops, such as many ornamental species.

In this work, a prototype of fertigation controller was designed for the management of container hardy ornamental nursery stocks irrigated with different water sources, including saline water. The prototype could schedule irrigation, alternatively, as a time clock system, or using a soil moisture dielectric sensor, or by a crop evapotranspiration (ET) model. In addition, the prototype could monitor the salinity in the root zone using either a dielectric sensor capable of measuring both substrate moisture and bulk electrical conductivity (EC), or a probe measuring the EC of the water draining from the containers. Excessive salinization of

the containers irrigated with saline water was automatically prevented by the adoption of a series of measures: irrigation with fresh water or a mixture of fresh water and saline water; increase of irrigation dose; reduction of fertilizer concentration in the nutrient solution delivered to the crop. The system was tested in a series of experiments conducted in Pistoia (Italy) between 2008 and 2010 with two ornamental species: *Photinia* × *fraseri* Dress and *Prunus laurocerasus* L.. When irrigation with fresh water was scheduled with the dielectric sensor or the ET model, seasonal water use and the loss of both N and P were reduced by 17% to 84% compared with the timer-controlled irrigation. The control of saline water irrigation using either the dielectric sensor or the EC probe mitigated the salinity-induced growth inhibition in both species; however, it did not prevent the occurrence of leaf damages (leaf scorch) on *Prunus* plants, which were unmarketable at the end of growing season. In contrast, in the more salt-tolerant *Photinia* plants, the use of the prototype resulted in a fresh water saving of 51% to 73% and all plants were classified in the top market quality category.

Abstract

The objective of this study was to design and test a prototype fertigation controller for the management of container ornamental nursery stocks irrigated with different water sources, including saline water or reclaimed municipal/industrial wastewater. The prototype could schedule irrigation in various ways, i.e. as a time clock, or by means of a soil moisture dielectric sensor, or using a crop evapotranspiration (ET) model. The prototype also monitored the salinity in the root zone using a dielectric sensor that measured both substrate moisture and electrical conductivity (EC), or a probe measuring the EC of the water draining out of the containers. Excessive substrate salinization of the containers irrigated with saline water (containing 10 mM of sodium chloride) was prevented by the automated adoption of a series of measures: irrigation with fresh water or a mixture of fresh water and saline water; progressive increase of irrigation dose for each event, and progressive reduction of fertilizer concentration in the nutrient solution delivered to the crop. The system was tested in three experiments conducted in Pistoia (Italy) between 2008 and 2010 with two ornamental species: *Photinia* × *fraseri* Dress (a salt-medium tolerant species) and *Prunus laurocerasus* L. (a salt-sensitive species). When irrigation with fresh water was controlled with a dielectric sensor or an ET model, total irrigation water use and the loss of both N and P were reduced by 17 % to 84% compared with the time-controlled irrigation. The sensor-based control of saline water irrigation reduced the salinity effects on dry matter accumulation in both species; however, it did not prevent the occurrence of leaf damages (leaf scorch) on *Prunus* plants, which were unmarketable by the end of growing season. On the contrary, no leaf damages were visible on Photinia plants irrigated with saline and/or fresh water, such that all were classified in the top quality market category. The controller developed in this work could be used in commercial nurseries to improve profitability and sustainability of container hardy ornamental nursery stocks production.

Keywords:

- Evapotranspiration model
- Irrigation scheduling
- Nutrient leaching
- Salinity stress
- Soil moisture sensor

Nomenclature

Symbol or abbreviation	Unit	Description
ε	$F \cdot m^{-1}$	Permittivity
CRF		Controlled release fertilizer
EC	$dS\ m^{-1}$	Electrical conductivity
EC_B	$dS\ m^{-1}$	Bulk electrical conductivity of substrate
EC_{DW}	$dS\ m^{-1}$	Electrical conductivity of drainage water
EC_{IW}	$dS\ m^{-1}$	Electrical conductivity of irrigation water
EC_{NS}	$dS\ m^{-1}$	Electrical conductivity of nutrient solution
EC_{PW}	$dS\ m^{-1}$	Electrical conductivity of substrate pore water
ET	mm	Crop evapotranspiration
ET_D	$mm\ day^{-1}$	Daily crop evapotranspiration
ET_0	mm	Reference evapotranspiration
FW		Fresh water (groundwater)
K_C	dimensionless	Crop evapotranspiration coefficient
K_S	dimensionless	Irrigation scheduling coefficient
MODEL		Evapotranspiration model-based irrigation scheduling
MW		Mixed water (a mixture of fresh water and saline water)
SMS		Soil moisture sensor-based irrigation scheduling
SSI		Salinity stress index
SW		Saline water
TIMER		Timer-based irrigation scheduling
VWC	$m^3\ m^{-3}$	Substrate volumetric water content
WSF		Water soluble fertilizer

1. Introduction

Due to the application of the ‘green city’ concept to urban development, the production and marketing of landscaping (ornamental) plants has increased in the last decades (Di Vita et al., 2015) and the plant nursery industry has become an important horticultural sector in many countries such as China, The Netherlands, the United States and Italy (AIPH, 2011).

Hardy ornamental nursery stocks are generally produced with considerable applications of water and agrochemicals, typically resulting in pollution (Majsztrik et al., 2011; Lea-Cox, 2012). In Europe, one of the major production areas for hardy ornamental nursery stocks is situated around the town of Pistoia in Tuscany, Italy. In Pistoia, there are more than 1000 wholesale nurseries spread on a total surface of 5400 ha: in the last decades, container cultivation has been increasingly used (covering at present approximately 1500 ha; Incrocci et al. 2014). Overhead sprinkler irrigation is commonly used for containers smaller than 5–7 L while micro-irrigation is applied to larger containers. Annual irrigation water use ranges from 1000 m^3 ha^{-1} in soil-bound crops to 10000-15000 m^3 ha^{-1} in container crops (Marzialetti and Pardossi, 2003; Pardossi et al., 2004), as also reported for nurseries in other countries [e.g. U.K. (Grant et al., 2009) and Florida (Beeson et al., 2004)].

Container hardy ornamental nursery stocks are often over-irrigated because of inaccurate scheduling, which is generally based on growers’ experience; a simple time clock system (timer) is commonly used for automated irrigation. In Pistoia production area, groundwater is the main source of irrigation water for nursery industry and annual irrigation water use is more than 14 million m^3 against an urban water use of less than 8 million m^3 (Incrocci et al., 2014). Current legislation on water resources (e.g. European Water Framework Directive; The Council of the European Communities, 2000) and the competition for water between agriculture and other users, such as population and industries, will affect the future development of hardy ornamental nursery stocks production in Pistoia. The design of an efficient irrigation management system as well as the possibility to use treated (reclaimed) wastewater derived from municipal or industrial activities is therefore crucial for nursery industry.

Irrigation with treated wastewater is a widespread practice in urban and peri-urban areas in many regions, especially in developing countries (Gatto D’Andrea et al., 2015; Marinho, 2013). The concentration of salts in wastewater streams varies considerably over time and depends on inputs into the sewer. Sewage with a high industrial input tends to be more saline than municipal sewage (Hamilton et al., 2007). Generally, treated wastewaters have electrical conductivity (EC) ranging from 600 to 1700 μS cm^{-1}, with a high proportion of sodium content (3-10 mol m^{-3}) relative to other cations (i.e. Ca and Mg) and its use for irrigation can induce crop salinity stress and/or crop sodium toxicity (e.g. Wu et al., 1995; Hamilton et al., 2007). In Pistoia and its neighboring areas, around 13 and 12 million m^{3} year^{-1} of municipal and industrial treated wastewater, respectively, are available and could be beneficially utilized by local agriculture, including nursery industry. The EC values range from 440 to 940 μS cm^{-1} for the former and from 500 to 1600 μS cm^{-1} for the latter, with a sodium and chloride content ranging from 2 to 10 mol m^{-3} (Lubello et al., 2004; Gori et al., 2008).

Many ornamental species are very sensitive to salinity stress. Generally, the first response of plants to salinity stress is a decrease of growth and leaf area, mainly due to the reduction in water supply to leaf cells, caused by the osmotic effect of salt on the root zone. The salinity buildup in the root zone is associated with ion toxicities or nutritional deficiencies that can produce damaged tips, marginal leaf burns, leaf chlorosis and necrosis (leaf scorch): in ornamental plants, these symptoms can strongly reduce the market value of these plants, since the decorative and aesthetic characteristics are fundamental for their quality (Cassaniti et al, 2012).

The application of excess water is a simple method to leach salts from the root zone and reduce the adverse effects of saline water irrigation on salt-sensitive plants, in particular when grown in containers. Over-irrigation results, however, in loss of water and fertilizers, which are leached into the soil and are likely to cause ground-water pollution. The actual real-time value of the salinity of the growing medium (soil or substrate) could be used to guide decision making about irrigation frequency and dosage in order to increase irrigation efficiency and reduce water runoff and nutrient loss. In container cultivation, for instance, the electrical conductivity measured in the aqueous extract of substrate or in the water drained out of the container could be used to provide real-time feedback for irrigation decisions and to adjust the EC of the irrigation water with the aim of preventing salinity build-up in the root zone. Commercially available dielectric sensors can monitor both water content and bulk EC (EC_B) of the growing medium (Pardossi et al., 2009; Lea-Cox, 2012). These sensors can be applied for the automated control of irrigation and fertigation of container crops, in particular when saline water is used.

The control of irrigation in container crops based on substrate salinity has received little attention; to our knowledge, only a few papers have been published on greenhouse crops (e.g.: Stanghellini et al., 2003; Scoggins and van Iersel, 2006; Sanchez-Guerrero et al., 2009;

Valdés et al., 2014, 2015a) and no work has been conducted on container hardy ornamental nursery stocks.

The main goal of this work was to develop a prototype fertigation controller to be used in the nursery industry for the management of containers irrigated with different water sources, including water with high sodium content such as saline- or treated waste-water. The prototype implemented different irrigation scheduling methods and procedures to prevent the occurrence of crop stress due to the salinity build-up in the substrate when saline water was used. The prototype could assess the salinity in the root zone using a dielectric sensor capable of measuring substrate moisture and EC_B, or a probe measuring the EC of runoff water (EC_{DW}). The control system was tested in three experiments conducted in Pistoia (Italy) between 2008 and 2010 with two species grown in hardy ornamental nursery stocks. This system could be used to reduce the consumption of fresh water and the pollution associated with nutrient loss with water runoff.

2. Materials and methods

2.1. Experimental site

The work was conducted in Pistoia, Italy (latitude: 43°55'9" N; longitude: 10°54'27" E) between 2008 and 2010. Mean values of daily air temperature, global solar radiation and reference evapotranspiration (ET_0) were similar in all the experiments and differences in season-cumulated ET_0 were principally due to the different length of growing seasons (Table 1, Fig. 1). The average rainfall and air temperature in the experimental periods (2008-2010) were 151.1 mm and 22.7 °C, respectively (source: www.cespevi.it/meteost.htm).

2.2 Plant material and growing technique

Two commercially important species were selected for their similar water needs and different sensitivity to salinity-induced leaf scorch, as found in a previous work (P. Marzialetti and A. Pardossi, unpublished results): *Photinia × fraseri* Dress cv. Red Robin (red tip photinia, tolerant) and *Prunus laurocerasus* L. cv. Novita (cherry laurel or English laurel; sensitive).

One-year old rooted cuttings of the two species, which had been grown in 1.8-L plastic pots (diameter 14 cm; height 12 cm), were transplanted in April and cultivated outdoors until October in 9.6-L black plastic cylinder containers (diameter 24 cm; height 21.5 cm) placed on a gravel bed. Each container held one plant and was irrigated with two drippers with a discharge rate of 6.0 L h^{-1}. Crop density was 2.4 plant m^{-2}.

Plants were cultivated according to the standard growing practice in the region of Pistoia. For instance, both species were pruned in July (to promote bottom branching) and fertilized using water-soluble fertilizers (WSF) dissolved in the irrigation water and/or controlled-release fertilizers (CRF) incorporated in the substrate before transplanting.

Substrate was a peat-pumice mixture (1:1, v:v), which is widely used in Pistoia for its good aeration and fast water percolation. Bulk density, porosity and water retention curve of the substrate were determined by an external laboratory (Laboratorio MAC, Vertemate con Minoprio, Como, Italy) using the CEN method (CEN, 2011). The values of VWC at 1.0, 3.0, 5.0, 7.5, 10.0, 15.0 and 20.0 kPa suction were 0.541, 0.414, 0.367, 0.355, 0.329, 0.328 and 0.327 m^3 m^{-3}, respectively. Bulk density, porosity of the substrate, container water capacity, and plant available water were 490 kg m^{-3}, 80.6%, 4.4 L pot^{-1}, and 1.8 L pot^{-1}, respectively. The container available water is here defined as the difference between the water content calculated at 0 and −10 kPa matric potential at the bottom of the container itself (Incrocci et al, 2014).

In each experiment, the substrate was enriched (5.0 kg m^{-3}) with CRF (Osmocote Exact Standard 15-9-11, longevity of 8-9 months, Everris International B.V., Geldermalsen, The Netherlands). Substrate volume averaged 7.7 L pot^{-1}, which consisted of approximately 75% of new substrate, the rest being the rooting medium. Therefore, the amounts of N and P supplied with substrate were 103.9 and 27.3 kg ha^{-1}, respectively.

The standard nutrient solution was prepared dissolving a WSF (Universol Blue 18-11-18, Everris International B.V. Geldermalsen, The Netherlands) in the irrigation water at a concentration of 250 mg L^{-1}. Two sources of irrigation water were used in all the experiments: fresh and saline water with 0.5 and 1.5 dS m^{-1} EC (named EC_{IW}), respectively. Saline water (SW) was prepared by adding 10 mol m^{-3} (588.4 mg L^{-1}) NaCl to fresh water (FW) to simulate the availability of treated municipal/industrial wastewater potentially available in Pistoia district. The EC of the nutrient solution (EC_{NS}) was 0.80 or 1.80 dS m^{-1}, depending on EC_{IW}; the concentrations of N, P and K were 44.9, 12.1 and 37.4 mg L^{-1}, respectively. In all the experiments, the pH of irrigation water was continuously measured by a pH probe connected to the prototype and automatically adjusted to 6.0 with sulphuric acid.

2.3 Description of the fertigation controller

The prototype was developed from an existing commercial fertigation device (MCNET II, Spagnol Greenhouse automation, Vidor, Italy) and could manage the irrigation of 16 separate plots using different water sources and salinity control strategies (see next section). The prototype automatically prepared the nutrient solution by injecting concentrated WSF and acid solutions from two stock tanks into the raw water at a rate depending on the target EC and pH, measured with a temperature-compensated EC probe (ECDCC/1, EMEC Ltd, Bologna, Italy) and a pH glass electrode (Hanna Instruments Italia, Italy), respectively. The device could be operated by a personal computer, either locally or remotely via the Internet; it was connected to a weather station and two different types of sensors to monitor root zone salinity: a dielectric sensor (WET™ Delta-T Devices Ltd, Burwell, Cambridge, United Kingdom) measuring volumetric water content (VWC) and EC_B and a probe (ECDCC/1, EMEC, Bologna, Italy) measuring the EC of drainage water (EC_{DW}). The pins of the WET™ sensor were placed in the substrate between 3.5 and 5 cm from the pot wall, and between 4 and 12 cm from the bottom. The WET™ sensor measures permittivity (ε), EC_B and temperature simultaneously in the same volume of soil or substrate (Balendonck et al., 2004; Pardossi et al., 2009). In order to avoid the influence of VWC on the measurement of EC_{PW} with the dielectric sensor, the system used only the EC_B readings at full container water capacity, occurring when the water runoff from the pots was virtually terminated (Incrocci et al., 2009). Starting from an earlier calibration for the peat-pumice mixture (Incrocci et al., 2009), permittivity and EC_B were tested at the beginning of each growing season at the container capacity, and converted, to VWC and pore water EC (EC_{PW}), respectively, using the following equations:

$$VWC = 0.0594 + 0.0230 \cdot \varepsilon - 0.0002 \cdot \varepsilon^2 \qquad (R^2 = 0.96) \qquad (1)$$

$$EC_{PW} = 4.11\ EC_B \qquad (R^2 = 0.90) \qquad (2)$$

The EC_B was calculated as the average of three consecutive measurements performed 10, 20 and 30 min after the end of each irrigation event. The same procedure on data acquisition was used for EC_{DW} measured with the EC probe. The EC probe measured EC_{DW} in a small reservoir (approximately 0.1 L) connected to a collecting tray with four plants. The whole apparatus was designed to minimize water evaporation and the influence of rainfall and of the leachate of previous irrigations.

2.4 Description of the irrigation and salinity control software

The software installed in the prototype was able to (see figure S1 in the supplemental material): i) schedule irrigation, either as a time clock controller (TIMER), or by measuring the substrate VWC with the dielectric sensor (SMS), or by using a crop evapotranspiration (ET) model (MODEL); ii) maintain the EC_{PW} or EC_{DW} below a pre-set threshold to prevent the occurrence of crop salinity stress. When operating in the SMS or MODEL mode, irrigation was scheduled to maintain a pre-irrigation substrate water deficit corresponding to a crop-specific fraction of the total available water (Incrocci et al., 2014). Since the *Photinia* is less sensitive to water stress than *Prunus*, we decided to use the same pre-irrigation substrate water deficit, fitted on *Prunus,* for both species. The irrigation dose was determined by multiplying the planned pre-irrigation substrate water deficit (L pot^{-1}) by a scheduling coefficient (K_S). This coefficient is a measure of the excess water applied to prevent salt accumulation in the substrate and to account for non-uniform water application (Rolfe et al., 2000). The Ks was dynamically modulated by fertigator prototype according to the container salinity build-up as described below.

In the SMS mode, the containers were irrigated whenever the substrate VWC, measured by the sensor, dropped below a threshold. In our work, the VWC was 0.52 m^3 m^{-3} (-1.3 kPa matric potential as average of the substrate volume monitored by the sensor), which corresponded to a pre-irrigation substrate water deficit of 38-42% of the available water, which was determined gravimetrically during the first week of each experiment as previously reported (Incrocci et al., 2014).

In the MODEL mode, irrigation was automatically activated whenever any predicted value of cumulated ET since the last irrigation exceeded the target pre-irrigation substrate water deficit. The hourly rate of ET was estimated for each species as the product of ET_0 times the crop coefficient (K_C), which could be manually entered into the computer by the user. Reference evapotranspiration was calculated from measurements of air temperature and humidity, wind speed and global radiation using an hourly equation developed by the California Irrigation Management Irrigation System (CIMIS) and calibrated in the summer climatic conditions of Pistoia (Bacci et al. 2008). In a previous paper (Incrocci et al. 2014), a correlation between leaf area index (LAI) and plant height for both species was found (the determination coefficients were 0.72 and 0.78 for *Prunus* and *Photina* plants, respectively). Moreover a significant relationship ($P \leq 0.01$) between LAI and Kc was also assessed. Combining the two correlations, Kc had been estimated directly from plant height, and a good correspondence between predicted and measured daily crop evapotranspiration had been found (determination coefficients 0.77 and 0.75 respectively for *Prunus* and *Photinia* plants). Thus, in this work, K_C was weekly calculated using the average plant height (H; m) of 10 plants for each irrigation sector using the equations reported by Incrocci et al. (2014):

$$\textit{Prunus}: K_C = 0.328\ (2.711\ H - 0.426) \tag{3}$$

$$\textit{Photinia}: K_C = 0.346\ (3.152\ H - 0.594) \tag{4}$$

In order to prevent the occurrence of crop salinity stress, the controller calculated a salinity stress index (SSI) defined as the number of consecutive times that the EC of substrate pore water (EC_{PW}) or drainage water (EC_{DW}) surpassed a threshold. EC_{PW} or EC_{DW} were measured shortly after each irrigation event. Whenever EC_{PW} or EC_{DW} reading surpassed the threshold, the salinity stress index increased by one unit; it decreased by one unit when the measured EC remained below the threshold. The salinity stress index was reset to zero if a number of successive EC readings were lower than the threshold.

In order to counter-act the substrate salinization, the prototype could apply three different salinity mitigation actions, each with different level of intensity: 1) the increase of standard irrigation dose; 2) the increase of fresh/saline water (FW/SW) mixing ratio in the irrigation water; 3) the reduction of water soluble fertilizer concentration in the nutrient solution.

The user must define for each irrigation sector a specific salinity control procedure: this means that for each SSI, the user must set the combination and the intensity of the salinity mitigation actions that the prototype will adopt in the next irrigation . More explicitly, after each irrigation, the prototype calculate the SSI for each irrigation sector; according to the salinity control procedure insert by the customer and the calculated SSI value, the prototype will adopt a precise irrigation dose, the FW/SW ratio and the WSF content of irrigation water. The EC threshold, the maximum limit of the salinity stress index, and the number of EC readings - to reset the salinity stress index - could be changed by the user.

In our work, the threshold of EC_{PW} or EC_{DW} were set to 2.5 and 2.0 dS m^{-1}, respectively; these values were considered the maximum tolerable salinity level for the ornamental species under investigation. The maximum limit of the salinity stress index was set to 10 units in consideration of the expected irrigation frequency (1-3 irrigations per day); the salinity stress index was reset to zero after three successive EC readings below the threshold.

2.5 Experimental design

Different irrigation treatments were compared in each experiment (Table 2). Each irrigation treatment was applied to 72 plants of each shrub species, which were grown in four blocks of 18 plants arranged in double row. The irrigation with fresh water (FW) under the control of a timer was included in all the experiments as the “grower” control (FW-TIMER). In this treatment, irrigation was activated once or twice per day (10.00 a.m. and/or 04.00 p.m.) and irrigation dose (1.90 to 2.40 mm) was adjusted every one or two weeks to account for variations in climatic conditions and plant dimensions according to the instructions from a local nurseryman. He ignored how irrigation was scheduled in the other treatments. Irrigation was switched off on rainy days in all the treatments.

During the three experiments, we tested the effects on the plant growth, water consumption and nitrogen and phosphorous losses when different water sources, irrigation scheduling methods, and EC probes were applied. For a better understanding of the experiment plan by the reader, the acronym of each treatment in all experiments identifies: i) the source of irrigation water (FW= fresh water; SW=saline water and MW= where SW, FW or a mixed of both, was automatically decided by the prototype, according to the SSI calculated after the last irrigation and the salinity control strategy set by the user); ii) the scheduling irrigation method applied (TIMER= using a clock-time method; SMS= the irrigation was controlled measuring the substrate VWC by a WET^{TM} sensor; MODEL= the irrigation was scheduled using an evapotranspiration method, based on the plant height); iii) the type of EC probe adopted to calculate the SSI (EC_{PW} or EC_{DW} if the SSI is calculated using a dielectric sensor or a drainage EC probe, respectively).

The first experiment was conducted in 2008 on *Prunus* (**experiment 1**) with the main goal to check the correct operation of the prototype. Three treatments were compared: i) FW-TIMER; ii) FW-SMS-EC_{PW} irrigated with fresh water and iii) MW-SMS-EC_{PW} irrigated with a mixture of fresh and saline water (MW), both under the control of a dielectric sensor (Table 2). This sensor was placed in one of 10 plants of cherry laurel that had been selected at transplanting for uniform size. Daily ET of these plants was gravimetrically monitored in two weeks before the start of observations and the plant with the ET closest to the average value was used as guide plant. The salinity control strategy implemented in the prototype to prevent salinity build-up in the substrate irrigated with fresh water or a mixture of fresh and saline water consisted initially in the reduction of WSF concentration (when the SSI is equal to 1 and 2), then in progressive increase of the FW/SW ratio (only in the MW-SMS-EC_{PW} treatment, SSI from 3 to 6), and finally in the increase of irrigation dose (SSI from 7 to 10; Table 2 and 3). Since in this experiment, the amount of WFS added to the various treatments resulted quite different with possible effects on plant growth, in the second and third experiment the amount of WFS was kept constant to all treatments.

Experiment 2 was conducted with *Prunus* to compare different water sources, scheduling irrigation methods (TIMER vs SMS), and salinity control procedures. The treatments were the following (Tables 2 and 3): i) and ii) irrigation with fresh water or saline water, respectively, under the control of a timer (FW-TIMER and SW-TIMER); iii) irrigation with fresh water under the control of a dielectric sensor (FW-SMS-EC_{PW}); iv and v) irrigation with a mixture of fresh and saline water (MW) under the control of a dielectric sensor with two salinity control strategies (MW-SMS-EC_{PW}1 and MW-SMS-EC_{PW}2). The MW-SMS-EC_{PW}1 strategy, aimed to reduce total water use and thus, the drainage water and nutrient losses. In this treatment the prototype used saline water until the SSI remained equal to zero. When the SSI increases, the first mitigation action applied was the progressive increase on the use of FW with respect to SW use (SSI from 1 to 3), and as second the increase of the irrigation dose of FW (SSI from 4 to 10). The goal of the second salinity control strategy (MW-SMS-EC_{PW}2) was to use saline water as much as possible in order to save fresh water: in this case, the sequence of the two mitigation actions described in the previous treatment were reversed (SSI= 1-3 and 4-6 progressive increase of irrigation dose and fresh water use, respectively) . In TIMER and SMS treatments, irrigation was scheduled as in experiment 1.

The main goal of **experiment 3** was to compare two different approaches to monitor root zone salinity: the measurement of EC_{PW} or EC_{DW}. The experiment was conducted with *Prunus* and *Photinia* and included the following treatments: i) FW-TIMER; ii) and iii) irrigation with fresh or saline water scheduled according to ET predictions (FW-MODEL and SW-MODEL); iv and v) irrigation with saline water or a mixture of saline and fresh water (MW) under the control of the ET model, and where the calculation of SSI was obtained by the measurement of EC_{PW} (by a dielectric sensor, MW-MODEL-EC_{PW}) or EC_{DW} (by EC probe put in the drainage water collector, MW-MODEL-EC_{DW}). In both these MW treatments, the salinity control strategy applied had the goal to reduce the total water use (the same tested in the experiment 2, see Tables 2 and 3).

2.6 Measurements

In all the experiments, daily crop ET, the volume and the nutrient concentration of both irrigation and water runoff were measured in individual plants on 16, 17 and 13 different days over the season 2008, 2009 and 2010, respectively. These days were carefully chosen in order to be representative of the average climate conditions recorded in the last six-seven days before the measurement. Four plants of each species were sampled from each irrigation treatment (one plant per block).

Each plant was insert into a larger bucket, with a distance of 5-6 cm to the bottom, in order to collect all drainage produced during the irrigation day, avoiding the contact between the drainage water and the bottom of the containerized plant. The whole system (bucket + the potted plant) and the only bucket was weighted at the 8.00 A.M. and after 24 h; successively, the drainage water present in each bucket was sampled and the flow of each dripper of the sampled plants were assessed, in order to calculate exactly the irrigation dose for each pot. In addition, a flow-meter was installed after the electrovalve of each irrigation sector, and for every selected day, a pot-dripper coefficient was calculated as the ratio between the pot irrigation dose and the total irrigation water applied. Finally, the crop ET, the drainage water and the leaching fraction was calculated as reported by Incrocci et al. (2014).

The N and P concentrations were assessed in the collected drainage samples using spectrophotometric analytic methods, as described by Massa et al. (2010).

The sampling days marked the beginning and the end of each sub-period (roughly 7-10 days). For each species and in all the treatments, the balance for water, N and P were computed on the four selected plants by cumulating the amounts determined for each sub-period, as following:

- the irrigation water use was obtained multiplying the irrigation water applied to the sector - measured by the flow-meter times the mean value of initial and final pot-dripper coefficients;
- the drainage amount calculated as the latter irrigation water use multiplied by the mean of initial and final measured leaching fractions;
- the amount of estimated N and P leaching computed as the latter drainage amount multiplied by the mean of initial and final measured N and P concentrations, respectively.

These data calculated for each selected plants were converted into millimetres or kg ha^{-1} considering a density of 2.4 containers m^{-2}.

At the end of each experiment, the four selected plants for each treatment were sampled for destructive measurements of leaf area index and shoot dry mass (Incrocci et al., 2014). On 10 plants for each treatment, we determined the percentage of leaves with an overall scorched area larger than approximately 5% of the total leaf area. Plant market quality was also evaluated at the end of the experiment 2 and 3as a subjective combination of plant growth and the appearance of foliage and root system. Two local nurserymen assessed the quality of 12 plants randomly sampled from each treatment; they ignored how each plant had been irrigated.

2.7 Statistical analysis

The differences between irrigation treatments were tested for each species using one-way analysis of variance (ANOVA). Mean values were separated using LSD test. Statistical analysis was performed with Statgraphics Plus 5.1 (StatPoint, Inc., Herndon, VA , USA).

3. RESULTS

3.1 Experiment 1

In this experiment, TIMER (control) containers were irrigated every day except on two days because of rain, whereas treatment FW-SMS-EC_{PW} and MW- SMS-EC_{PW} faced only one day without irrigation (day 17 and 29, respectively). TIMER treatment involved far more irrigation events (210) than FW-SMS-EC_{PW} (164) and MW-SMS-EC_{PW} (120). During the season, WSF was always added to the irrigation water for FW-TIMER treatment, while was not added on 56 and 96 occasions in the FW-SMS-EC_{PW} and MW-SMS-EC_{PW} treatments, respectively.

In TIMER containers, the leaching fraction averaged 34.7% against 17.6% or 18.7% in those of FW-SMS-EC_{PW} and MW-SMS-EC_{PW} plots, respectively (Table 4). In the latter two treatments, the total irrigation water use and water runoff were reduced by 32% and 64%, respectively, compared with the control (Table 4). The use of fresh water decreased by 55% in MW-SMS-EC_{PW} treatment.

As expected, EC_{NS} and EC_{PW} measured at each irrigation event were generally higher in containers irrigated with a mixture of fresh and saline water than in the other treatments (Fig. 2). In the control, mean EC_{PW} remained invariably below the threshold (2.5 dS m^{-1}), which however was surpassed frequently and for several consecutive days both in FW-SMS-EC_{PW} and MW- SMS-EC_{PW}; average salinity stress index was 1.7 and 4.3, respectively (Fig. 2).

The average concentration of N and P in the water runoff collected periodically during the season was lower in the SMS treatments than in the control, in particular when plants were irrigated with a mixture of fresh and saline water (Table 4). When irrigation was controlled with the dielectric sensor, we found a remarkable decrease in total nutrient application both for N and P (-21% in FW-SMS-EC_{PW} and -56% in MW-SMS-EC_{PW}) and loss (-71% for N and -66% for P in FW-SMS-EC_{PW}; -73% for N and -78% for P in MW-SMS-EC_{PW}) with respect to the control (FW-TIMER, Table 4).

Daily ET was slightly but significantly reduced (-15%, on average) in the SMS treatments with respect to the control (Table 4). At the end of the experiment, no significant differences were found across the treatments for plant height; in contrast, LAI and shoot dry weight were significantly reduced in plants irrigated a mixture of fresh and saline water compared with those irrigated with fresh water (Table 4).

All the plants irrigated with a mixture of fresh and saline water showed severe leaf scorch; at the end of the experiment, 45% of the leaves on sampled plants were damaged. In contrast, leaf scorch did not affect any plant watered with FW.

3.2 Experiment 2

In 2008, the reduction of plant growth in treatment MW-SMS-EC_{PW} was associated with nutrient shortage resulting from many irrigations with WSF-free water (Tables 2 and 3). Therefore, in 2009 we tested two salinity control strategies that did not include the reduction of WSF concentration in the nutrient solution (Tables 2 and 3).

In this experiment, the control plants were not watered because of rain on 13 days whilst days without irrigation were 26 to 31 in the plants irrigated under the control of a dielectric sensor. The number of irrigation events was much greater in TIMER treatments (242) than in FW-SMS-EC_{PW} (162), MW- SMS-EC_{PW}1 (160) and MW- SMS-EC_{PW}2 (153) treatments.

In TIMER treatments, mean leaching fraction was 56%, on average, against 14.2%, 26.5% and 30.1% in FW-SMS-EC_{PW}, MW-SMS-EC_{PW}1 and MW-SMS-EC_{PW}2 treatments, respectively (Table 5). The application of the substrate moisture sensor for irrigation scheduling markedly reduced the total irrigation water use (-33% to -46%) and water runoff (-67% to -88%; Table 5) with respect to the control. The use of fresh water was greater in MW-SMS-EC_{PW}1 plants (85.9% of the total irrigation water use) than in MW-SMS-EC_{PW}2 plants (56.2%, Table 5).

The EC_{NS} and EC_{PW} measured at each irrigation event were higher in plants irrigated with saline water or a mixture of fresh and saline water than in those irrigated with FW; EC_{PW} was not measured in TIMER containers. The mean of periodical measurements of EC_{DW} during the season was also greater for containers irrigated with a mixture of fresh and saline water compared with the other treatments (Table 5). In containers irrigated with a mixture of fresh and saline water, mean EC_{PW} was above the threshold (2.5 dS m^{-1}) and the salinity stress index averaged 7.0 and 4.3 in MW-SMS-EC_{PW}1 and MW-SMS-EC_{PW}2, respectively (Fig. 3).

The use of dielectric sensor for irrigation scheduling decreased in all SMS treatments both the supply and the estimated leaching of N and P in comparison to TIMER treatments (Table 5). In FW-SMS-EC_{PW} treatment, the total use and loss of both N and P were markedly decreased with respect to the TIMER system (for example, -75% and -84% respectively for N and P leaching, Table 5). Irrigation with saline water significantly reduced daily ET, shoot dry weight and LAI with respect to the control (Table 5).

At the end of the experiment, the percentage of damaged leaves accounted for 64.1 % and 42.0 % in SW-TIMER and MW- SMS-EC_{PW}2, respectively (Table 5). According to two local growers, all the plants sampled from FW-TIMER, FW-SMS-EC_{PW} and MW-SMS-EC_{PW}1 plots were in the best market quality category; in contrast, SW-TIMER and MW-SMS-EC_{PW}2 plants were judged unmarketable due to leaf scorch.

3.3 Experiment 3

In this experiment, we tried to test a different approach to control the salinity build-up in the container without the use of soil moisture sensor: root zone salinity was assessed measuring either EC_{PW} or EC_{DW}.

In experiments 1 and 2, the values of EC_{DW} and EC_{PW} measured at the same irrigation event were not significantly correlated due to wide data scattering; however, the experimental mean values of EC_{DW} was 10% to 30% lower than the corresponding mean values of EC_{PW}. Therefore, in experiment 3 the threshold for EC_{DW} was set 2.0 dS m^{-1} instead of 2.5 dS m^{-1} for EC_{PW}, as in experiments 1 and 2.

In this experiment irrigation was based on a crop evapotranspiration model (reference evapotranspiration times a crop coefficient), in order to avoid the use of a soil moisture sensor, and at the same time to be tightly related to the plant water consumption for all the treatments, with the exclusion of the control (TIMER) treatment.

In the control treatment, *Prunus* plants were not watered because of rain on 19 days whereas MODEL plants were not irrigated in 33 days. The number of irrigation events was 132 and 83 in TIMER and MODEL treatments, respectively.

In TIMER containers, mean leaching fraction was 33.5% and ranged between 12.3% and 30.1% for those in MODEL treatments (Table 6). Irrigation water use and water runoff in FW-TIMER and in treatments irrigated with a mixture of fresh and saline water (MW) were similar and much higher than in FW-MODEL and SW-MODEL treatments (Table 6). The use of fresh water was greater in MW-MODEL-EC_{PW} than in MW-MODEL-EC_{DW}, but it was strongly reduced in both treatments (respectively, -51.1% and -34.5%) with respect to TIMER plot.

Mean values of EC_{PW} in MW-MODEL-EC_{PW} treatment and EC_{DW} in MW-MODEL-EC_{DW} were close to the threshold value (2.5 or 2.0 dS m^{-1}; Fig. 4). The salinity stress index average was 3.7 and 2.8 in MW-MODEL-EC_{PW} and MW-MODEL-EC_{DW}, respectively. The mean of periodical measures of EC_{DW} during the season was also greater for containers irrigated with saline water and with a mixture of fresh and saline water compared with those irrigated with fresh water (Table 6).

Compared with the control, ET-based irrigation scheduling with fresh or saline water treatment (FW-MODEL and SW-MODEL) reduced the total use (-17%) and loss (-53%) of N. Phosphorus was not considered in this experiment.

At the end of the experiment, no significant differences were found across the treatments for plant height and LAI while shoot dry biomass was significantly smaller in plants irrigated with saline water (Table 6). The number of damaged leaves was negligible in fresh water treatments whereas accounted for 72.8%, 25.7% and 22.7% in SW-MODEL, MW-MODEL-EC_{PW} and MW-MODEL-EC_{DW}, respectively (Table 6). The two evaluators judged all the plants irrigated with saline water or with a mixture of fresh and saline water unmarketable while those irrigated with fresh water were ranked in the first quality category.

Very similar results in terms of water and N balance, and plant growth, were found in *Photinia* (Table 7; Fig. 4). This crop was irrigated more frequently (172 times in the control and 130 times, on average, in MODEL plots) than *Prunus* as a result of greater size. For instance, in MODEL plots N loss was reduced by 24% to 53% with respect to the control. In contrast to *Prunus*, no *Photinia* plant showed scorched leaves and the two evaluators ranked all the sampled plants in the first quality market category (Table 7).

4. DISCUSSION

4.1. Irrigation scheduling

In this work, irrigation was scheduled using a time clock system (TIMER), a soil moisture sensor (SMS) or a simplified ET model (MODEL). The first one is the most used system in commercial nurseries in many countries in consideration of its simplicity and low cost (e.g. Grant et al., 2009; Incrocci et al., 2014; Lea-Cox, 2012; Majsztrik et al. 2011). In our work, the leaching fraction of TIMER treatments was between 33.5% (Table 6) and 62.2 % (Table 5). These figures are within those recorded in commercial nurseries in Pistoia (Marzialetti and Pardossi, 2003) and in other countries for instance in U.K (Grant et al. 2009) and in U.S.A. (Majsztrik et al., 2011).

In comparison to the TIMER treatment, the total irrigation water use decreased by 26%–46% in SMS (Tables 4 and 5) or MODEL (Tables 6 and 7) treatments, without significant differences on season-cumulative ET and dry matter production.

The reduction of the total irrigation water use in SMS and MODEL treatments could be attributed to a reduction of both irrigation frequency and leaching fraction (Tables 4, 5, 6, and 7), and not to a smaller irrigation dose, in agreement with previous findings (Incrocci et al., 2014). The lack of important effects on plant ET suggests that all the plants of both species received optimal irrigation in experiments 1-3.

Several authors had reported that the use of substrate moisture sensors or ET model for irrigation control decreased the total irrigation water use of container nursery crops without detriment to crop growth (e.g. Bacci et al. 2008; Grant et al. 2009 and 2012; Incrocci et al 2014; Lea-Cox et al., 2013).

The total irrigation water use depends on the length of the experimental period and on its climatic conditions (for example the seasonal cumulated rainfall and ET_0): normalized data for the experimental period length, being similar the daily ET_0 of the three experiments (see Table 1), showed that the SMS or MODEL -using only fresh water- reduced the amount of irrigation water in *Prunus* plants of 1.10, 1.98 and 0,66 mm day^{-1}, respectively for the 2008, 2009 and 2010 seasons, compared to control treatments (FW-TIMER).

Several authors reported that irrigation water scheduling is the most important issue to properly manage nutrients leaching in ornamental crop production (Grant et al., 2009; Lea-Cox, 2012; Majsztrik et al., 2011).

In *Prunus* plants, the SMS or MODEL irrigation scheduling reduced the normalized data of total N supply (0.56, 1.03 and 0.32 kg ha^{-1} day^{-1}) and estimated N leaching (0.25, 0.81, and 0.30 kg ha^{-1} day^{-1}), respectively for the 2008, 2009 and 2010 seasons, compared to control treatments (FW-TIMER). A similar trend was recorded for the phosphorus: the reduction of total P supply (0.14, and 0.31 kg ha^{-1} day^{-1}) and of estimated P leaching (0.05, and 0.26 kg ha^{-1} day^{-1}), respectively for the 2008, and 2009 seasons, compared to control treatments (FW-TIMER). We point out that in 2009 experiment the difference of supplied and leached nutrients were so high due to the large amount of irrigation water applied in FW-TIMER treatment: the normalized total irrigation water use was 4.35 mm day^{-1} in 2009, and 3.54 and 2.49 mm day^{-1}, in 2008 and 2010, respectively.

Our results pointed out that optimal irrigation scheduling reduce the environmental impact associated with nutrient emission mainly due to a reduction of water runoff.

4.2 Crop response to saline water irrigation

Plant tolerance to saline water irrigation is generally assessed from growth reduction. In ornamental plants, however, one should also consider the appearance of foliage, because salt stress can result in leaf damages that reduce their market value (Cassaniti et al. 2012, Valdés et al., 2015a, b). *Photinia* is classified as salt sensitive plant (Miyamoto et al., 2004) while *Prunus* is considered tolerant to salinity by some authors (Appleton et al., 2015) or sensitive by others (Hill et al., 2004). In our work, *Photinia* and *Prunus* exhibited a different response to NaCl salinity. In fact, saline water irrigation markedly reduced shoot growth in both species (Tables 5 and 6 for *Prunus*; Table 7 for *Photinia*) while leaf scorch was observed only in *Prunus.*

The irrigation control system developed in this work prevented the adverse effects of saline water irrigation in both species, as confirmed by the similar shoot dry mass, LAI and mean daily crop ET (Tables 4, 5, 6 and 7), with the exception of *Prunus* in the experiment 1 (MW-SMS-EC_{PW}). Growth reduction observed in the latter experiment, could be also attributed to the reduced amount of N and P supplied: in fact, the salinity control strategy had as first mitigation action the reduction of WSF. Many studies demonstrate that salinity can impair nutrient uptake in plants, thus reducing their growth (Grattan and Grieve, 1999; Cassaniti et al., 2012).

During the whole experimental period, two main salinity control strategies were tested for the possible use of saline water (or treated wastewater) on *Prunus* plants: the first strategy aimed at reducing the total irrigation water use (MW-SMS-EC_{PW}1), and the second at saving as much as possible the fresh water (MW-SMS-EC_{PW}2 in 2009; MW-MODEL-EC_{PW} or MW-MODEL-EC_{DW} in 2010). From a commercial point of view, for salt-sensitive species such as *Prunus*, only the first strategy was reliable, since the latter strategy resulted in large leaf damage percentages leading to an unmarketable production. As a matter of fact, the first strategy if compared to FW-SMS-EC_{PW} produced a reduction of fresh water consumption (2.41 and 2.37 mm day^{-1}, for MW-SMS-EC_{PW}1 and FW-SMS-EC_{PW}, respectively), and an increase of the total irrigation water use, the drainage water (2.81, 0.74 against 2.37, 0.34 mm day^{-1}, respectively), and the estimated total N leaching (0.42 against 0.27 kg ha^{-1} day^{-1}).

On the contrary, for more salt-tolerant species such as *Photinia*, the second salinity control strategy did not affect the market crop quality. The comparison of the average of MW-MODEL-EC_{PW}, and MW-MODEL-EC_{DW} with the FW-MODEL-EC_{PW} showed a reduction of the fresh water consumption (1.33 and 2.89 mm day^{-1}, respectively), and an increase of the total irrigation water use, and of the drainage water (3.50, 1.33 against 2.89, 0.54 mm day^{-1}, respectively), thus leading to an increase of the estimated total N leaching (0.44 against 0.28 kg ha^{-1} day^{-1}). These results mean that the second salinity control strategy led to an interesting fresh water saving (1.56 mm day^{-1}), associated with a light increase of N loss (0.16 kg ha^{-1}

day^{-1}). These findings are in agreement with the conclusions of Stanghellini et al. (2007). According to these authors, the production of salt-sensitive crops with moderately saline water required a great LF, thus resulting in a large environmental impact due to nutrient leaching.

4.3 Sensing root zone salinity

The WET™ sensor calculated the EC_{PW} from EC_B following the Hilhorst model (Hilhorst, 2000), taking in account the influence of substrate VWC. The Hilhorst calibration was labour–consuming, since it must be done at different substrate water contents. In order to simplify the calibration procedure, we had proposed to use a linear calibration between EC_{PW} and EC_B, using only the EC_B values recorded at the full container capacity, that in our experiments occurred after the end of irrigation events.

In this work, the pore water EC and the drainage EC values taken at the same time were poorly correlated. This was expected as the relationship between EC_{PW} and EC_{DW} in container crops is influenced by many factors such as: EC and ion content of irrigation water; leaching fraction; substrate VWC and cation exchange capacity; salt distribution in the root zone, which depends on the irrigation method, the use of controlled release fertilizers (since they may not be uniform within the pot), and the plant uptake of both water and nutrients (De Rijck and Schrevens, 1998; Incrocci et al., 2006; Sonneveld and Voogt, 2009).

Similar results were found in pot-grown plants of poinsettia and geranium by Valdés et al., (2014, 2015a). These authors found a significant linear regression between EC_{DW} and substrate EC_B, which in turn is linearly related to EC_{PW}. In our in well-hydrated substrate, EC_{PW} is approximately 4-fold bulk EC (see Eq. 2). According to Sonneveld and Voogt (2009), EC_{PW} of soilless substrate is generally higher than EC_{DW}: in our experiments, this statement was confirmed, since the seasonal average of the drainage EC measurements of each specific treatment was lower than the average of EC_{PW} values (from -10% to -30%). Therefore, different EC thresholds must be set when saline water irrigation is managed using a dielectric sensor buried in the substrate or a probe measuring EC drainage water. Sonneveld and Voogt (2009) had given some recommendation about the optimal EC of the nutrient solution present in the substrate for cut flower and ornamental crops (from 1.0 to 2.5 dS m^{-1}) and for fruit vegetable crops (from 2.5 to 5.5 dS m^{-1}).

The results of the experiment 3 confirmed that both the EC monitoring systems are reliable to avoid salinity build-up when the salinity mitigation strategy is used.

The main advantage of dielectric sensors is that they can measure both substrate VWC and

EC_{PW} and then could be also used to schedule irrigation. However, these sensors are expensive and need a substrate-specific calibration. In addition, the conversion of EC_B to EC_{PW} is influenced by substrate moisture (Incrocci et al., 2009, 2014) and, two or more sensors should be placed in the same irrigation sector because of possible sensor failure and/or the discrepancy in sensor readings between the monitored container(s) and the others. In the case of more than one sensor are used, a safety procedure must be embedded in the fertigation device, in order to signal an eventual malfunctioning to the grower.

However, in the last years some much cheaper dielectric sensors became available for growers, and in addition the calibration procedures can be by-passed using raw data readings taken at the desired substrate water content assessed empirically by the growers.

In contrast, EC probes are much cheaper, can be easily calibrated and monitor more than one container, as in our experiments. In principle, an EC probe could be immersed in the tank or basin collecting the water draining from the whole irrigation plot, thus providing very robust data about on root zone salinity. Finally, the use of EC probe combined to a scheduling irrigation based on evapotranspiration model can facilitate the management of saline water irrigation in the nursery industry.

5. CONCLUSIONS

In this study, we tested a prototype for management of container nursery crops irrigated with different water sources, including saline water. The system scheduled irrigation used different types of sensors to monitor weather conditions, substrate moisture and the salinity in the root zone. Scheduling irrigation with dielectric sensors or simplified evapotranspiration model reduced total irrigation water use by 24% to 46% and nutrient losses by 17% to 84% compared to the standard timer-based irrigation with fresh water. The adoption of salinity control procedures coupled with sensor or crop evapotranspiration scheduling method alleviated the adverse effects of saline water irrigation on plant growth in both *Prunus* and *Photinia*. However, in *Prunus* all the plants irrigated with saline water or most of those irrigated with a mixture of fresh and saline water were affected by leaf scorch at the extent that they were unmarketable at the end of growing season. In contrast, in the more salt-tolerant *Photinia* plants, the use of the prototype resulted in a fresh water saving of 51% to 73% and all plants were classified in the top market quality category. Thus, in our experimental conditions, the use of saline water joint to automatic salinity control strategies for the cultivation of salt-sensitive ornamental species resulted not suitable for the commercial nurseries, since it did not produce a saving in fresh water. Indeed, the tested procedure was very interesting for growing medium-salt tolerant ornamental crops (i.e. *Photinia* plants): in our case, the fresh water saving ranged from 51 to 65%. Sensor-based irrigation is not straightforward in commercial nurseries because they have many irrigation plots and produce hundreds of plant species with different water requirements and salinity tolerance. Wireless sensor network technology and smart irrigation controllers, such as the prototype developed in this work, could overcome these difficulties. The use of low cost EC probes, instead of more expensive dielectric sensors, and crop evapotranspiration models for irrigation scheduling can significantly reduce the investment cost of the whole control system. The prototype could also be used for greenhouse operations. The application of sensor-based fertigation is easier for container greenhouse production, where few and more uniform crops are generally grown, thus limiting the number of irrigation sectors.

Acknowledgements

This work was funded by three projects funded by European Commission (FLOWAID, 2006-2009, EU-FP6 contract no. 036958; www.Flow-aid.eu, Italian Ministry of Agricultural Policies (FLORPRO, 2007–2010) or Tuscany Regional Government (VIS, 2010–2012; www.cespevi.it/vis/vis.htm).

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Table 1. Basic information on the irrigation study conducted on hardy ornamental nursery stocks grown in container in Pistoia (Italy) between 2008 and 2010.

Experiment (Year)	**Planting date**	**Period of observations**	**Days of observations**	**Mean daily air temperature (°C)**	**Mean daily global solar radiation (MJ m^{-2})**	**Mean daily reference evapotranspiration (mm day^{-1})**	**Season-cumulated reference evapotranspiration (mm)**	**Season-cumulated rainfall (mm)**
1 (2008)	28 April	10 June – 9 October	122	22.3	19.8	3.62	441.4	55.6
2 (2009)	20 April	18 May – 7 October	143	23.4	20.0	3.73	533.3	159.3
3 (2010)	29 April	25 June – 5 October	103	22.5	19.6	3.42	352.3	238.4

Table 2. Description of irrigation treatments in different experiments conducted with hardy ornamental nursery stocks grown in container in Pistoia (Italy) between 2008 and 2010: crop species (*Photinia* x *Fraseri*; *Prunus laurocerasus*), water source (fresh water, FW; saline water, SW; a mixture of fresh and saline water, MW), irrigation scheduling method (time clock system, TIMER; soil moisture sensor, SMS; evapotranspiration model, MODEL); the input parameter for the salinity control procedures (electrical conductivity of substrate pore water, EC_{PW}, or EC of water runoff, EC_{DW}); the sequence of measures taken to prevent excessive salinization of the substrate. Other abbreviations: WSF, concentration of water soluble fertiliser in the irrigation water; FW/SW, the volumetric ratio between fresh water and saline water in irrigation; ID, irrigation dose. The symbols "↓" and "↑" indicate, respectively, a decrease or an increase in WSF, FW/DW and ID.

Exp. (Year)	**Crop species**	**Treatment name**	**Water source**	**Irrigation method**	**Input parameter for salinity control**	**Sequence of salinity control measures**
1 (2008)	*Prunus*	FW-TIMER	FW	TIMER	-	
		FW-SMS-EC_{PW}	FW	SMS	EC_{PW}	↓WSF; ↑ID
		MW-SMS-EC_{PW}	MW	SMS	EC_{PW}	↓WSF; ↑FW/SW; ↑ID
2 (2009)	*Prunus*	FW-TIMER	FW	TIMER	-	-
		SW-TIMER	SW	TIMER	-	-
		FW-SMS- EC_{PW}	FW	SMS	EC_{PW}	↑ID
		MW-SMS- EC_{PW} (1)	MW	SMS	EC_{PW}	↑FW/SW; ↑ID;
		MW-SMS- EC_{PW} (2)	MW	SMS	EC_{PW}	↑ID; ↑FW/SW
3 (2010)	*Prunus* and *Photinia*	FW-TIMER	FW	TIMER	-	-
		FW-MODEL	FW	MODEL	-	-
		SW-MODEL	SW	MODEL	-	-
		MW-MODEL- EC_{PW}	MW	MODEL	EC_{PW}	↑ID; ↑FW/SW
		MW-MODEL- EC_{DW}	MW	MODEL	EC_{DW}	↑ID; ↑FW/SW

Table 3. Description of salinity control procedures tested in different experiments with hardy ornamental nursery stocks grown in container in Pistoia (Italy) between 2008 and 2010 and irrigated using different water sources: fresh water (FW), saline water (SW) or a mixture of them (MW). Irrigation was scheduled using a pre-set program (TIMER), a dielectric moisture sensor (SMS) or the evapotranspiration model (MODEL). See text for details. The salinity control procedures differed for the FW/SW ratio in the raw water, the irrigation dose and the concentration of water soluble fertilizer (WSF) in the irrigation water for a given value of the

salinity stress index (SSI); the electrical conductivity (EC) of irrigation water before (EC_{IW}) and after nutrient addition (EC_{NS}) is also shown. The SSI is the number of consecutive times that the EC of substrate pore water (EC_{PW}) or drainage water (EC_{DW}), measured after each irrigation event, surpassed a threshold of 2.5 or 2.0 dS m^{-1}, respectively.

SSI	**FW/SW ratio**	**Irrigation dose (mm; seconds)**	**Nutrient content (kg m^{-3})**	**EC_{IW} (dS m^{-1})**	**EC_{NS} (dS m^{-1})**
FW-SMS-EC_{PW} (Experiment 1, 2008)					
0	100:0	2.00 (240 s)	0.250	0.50	0.80
1	100:0	2.00 (240 s)	0.125	0.50	0.65
2	100:0	2.00 (240 s)	0.00	0.50	0.50
3	100:0	2.10 (252 s)	0.00	0.50	0.50
4	100:0	2.20 (264 s)	0.00	0.50	0.50
5	100:0	2.30 (276 s)	0.00	0.50	0.50
6-10	100:0	2.40 (288 s)	0.00	0.50	0.50
MW-SMS-EC_{PW} (Experiment 1, 2008)					
0	0:100	2.00 (240 s)	0.250	1.50	1.80
1	0:100	2.00 (240 s)	0.125	1.50	1.65
2	0:100	2.00 (240 s)	0.00	1.50	1.50
3	33:67	2.00 (240 s)	0.00	1.17	1.17
4	67:33	2.00 (240 s)	0.00	0.83	0.83
5	100:0	2.00 (240 s)	0.00	0.50	0.50
6	100:0	2.00 (240 s)	0.00	0.50	0.50
7	100:0	2.10 (252 s)	0.00	0.50	0.50
8	100:0	2.20 (264 s)	0.00	0.50	0.50
9	100:0	2.30 (276 s)	0.00	0.50	0.50
10	100:0	2.40 (288 s)	0.00	0.50	0.50

To be continued

FW-SMS-EC_{PW} (Experiment 2, 2009)					
0	100:0	2.25 (270 s)	0.250	0.50	0.80
1	100:0	2.50 (300 s)	0.250	0.50	0.80
2	100:0	2.75 (330 s)	0.250	0.50	0.80
3	100:0	3.00 (360 s)	0.250	0.50	0.80
4	100:0	3.25 (390 s)	0.250	0.50	0.80
5	100:0	3.50 (420 s)	0.250	0.50	0.80
6-10	100:0	3.75 (450 s)	0.250	0.50	0.80
MW-SMS-EC_{PW}1 (Experiment 2, 2009)					
0	0:100	2.25 (270 s)	0.250	1.50	1.80
1	33:67	2.25 (270 s)	0.250	1.17	1.47
2	67:33	2.25 (270 s)	0.250	0.83	1.13
3	100:0	2.25 (270 s)	0.250	0.50	0.80
4	100:0	2.75 (330 s)	0.250	0.50	0.80
5	100:0	3.25 (390 s)	0.250	0.50	0.80
6-10	100:0	3.75 (450 s)	0.250	0.50	0.80
MW-SMS-EC_{PW}2 (Experiment 2, 2009)					
0	0:100	2.25 (270 s)	0.250	1.50	1.80
1	0:100	2.75 (330 s)	0.250	1.50	1.80
2	0:100	3.25 (390 s)	0.250	1.50	1.80
3	0:100	3.75 (450 s)	0.250	1.50	1.80
4	33:67	3.75 (450 s)	0.250	1.17	1.47
5	67:33	3.75 (450 s)	0.250	0.83	1.13
6-10	100:0	3.75 (450 s)	0.250	0.50	0.80
MW-MODEL-EC_{PW} and MW-MODEL-EC_{DW} (Experiment 3, 2010, *Photinia* and *Prunus*)					
0	0:100	2.00 (240 s)	0.250	1.50	1.80
1	0:100	2.42 (290 s)	0.250	1.50	1.80
2	0:100	2.83 (340 s)	0.250	1.50	1.80
3	0:100	3.25 (390 s)	0.250	1.50	1.80
4	33:67	3.25 (390 s)	0.250	1.17	1.47
5	67:33	3.25 (390 s)	0.250	0.83	1.13
6-10	100:0	3.25 (390 s)	0.250	0.50	0.80

Table 4. Influence of the irrigation treatments on the balance of water, nitrogen and phosphorus, mean daily crop evapotranspiration (ET) and some growth parameters of *Prunus laurocerasus L.* plants grown in container in Pistoia (Italy) in 2008 (Experiment 1). The electrical conductivity (EC) of irrigation water, drainage water and substrate pore water (EC_{DW}), and the leaching fraction are also shown. Plants were watered using different water sources: fresh water (FW), or a mixture (MW) of fresh and saline water in different ratio according to the level of substrate salinity build-up. Irrigation was automatically scheduled using a pre-set program (TIMER) or a dielectric sensor (SMS). In two treatments, measures were taken based on EC_{PW} to prevent excessive salinization of the substrate. Crop ET was gravimetrically measured on different dates during the growing season while growth parameters were measured at the end of the experiment. See text and Tables 2-3 for details.

Parameter	**FW-TIMER**	**FW-SMS-EC_{PW}**	**MW-SMS-EC_{PW}**
Total irrigation water use (IWU; mm)	432.0 A	298.0 B	288.5 B
Fresh water use (% of IWU)	100 A	100 A	45.1 B
Water runoff (mm)	149.9 A	52.5 B	53.9 B
Leaching fraction (%)	34.7 A	17.6 B	18.7 B
Irrigation water EC (dS m^{-1})	0.80 B	0.68 C	1.03 A
Drainage water EC (dS m^{-1})	0.81 C	1.21 B	1.47 A
Drainage water N concentration (mg L^{-1})	28.3 A	23.8 B	21.0 C
Drainage water P concentration (mg L^{-1})	6.7 A	6.5 A	4.1 B
Total N supply (kg ha^{-1})	317.9 A	249.9 B	139.2 C
Estimated total N leaching (kg ha^{-1})	42.4 A	12.5 B	11.3 B
Total P supply (kg ha^{-1})	79.5 A	62.8 B	34.3 C
Estimated total P leaching (kg ha^{-1})	10.1 A	3.4 B	2.2 B
Mean daily crop ET (mm day^{-1})	2.09 A	1.82 B	1.72 C
Plant height (m $plant^{-1}$)	0.70 A	0.64 A	0.67 A
Leaf area index (dimensionless)	2.74 A	2.5 AB	2.39 B
Shoot dry mass (t ha^{-1})	6.00 A	5.72 A	5.20 B
Leaf damage (%)	0.0 B	0.0 B	45.0 A

*In each row, mean values (n = 4) followed by the same letters are not significantly different ($P < 0.01$) according to LSD test.

Table 5. Influence of the irrigation treatments on the balance of water, nitrogen and phosphorus, mean daily crop evapotranspiration (ET) and some growth parameters of *Prunus laurocerasus L.* plants grown in container in Pistoia (Italy) in 2009 (Experiment 2). The electrical conductivity (EC) of irrigation water, drainage water and substrate pore water (EC$_{PW}$), and the leaching fraction are also shown. Plants were watered using different water sources: fresh water (FW) saline water (SW) or a mixture of fresh and saline water (MW), in different ratio according to the level of substrate salinity build-up. Irrigation was automatically scheduled using a pre-set program (TIMER) or a dielectric sensor (SMS). In three treatments, measures were taken based on EC$_{PW}$ to prevent excessive salinization of the substrate. Crop ET was gravimetrically measured on different dates during the growing season while growth parameters were measured at the end of the experiment. See text and Tables 2-3 for details.

Parameter	**FW-TIMER**	**SW-TIMER**	**FW-SMS-EC$_{PW}$**	**MW-SMS-EC$_{PW}$1**	**MW-SMS-EC$_{PW}$2**
Total irrigation water use (IWU, mm)	622.3 A	557.9 B	338.9 E	401.4 D	418.2 C
Fresh water use (% of IWU)	100 A	0 D	100 A	85.9 B	56.2 C
Water runoff (mm)	386.8 A	280.3 B	48.0 E	106.4 D	125.8 C
Leaching fraction (%)	62.16 A	50.24 B	14.16 E	26.51 D	30.08 C
Irrigation water EC (dS m^{-1})	0.80 E	1.78 A	0.79 D	1.11 C	1.45 B
Drainage water EC (dS m^{-1})	1.19 D	2.80 A	1.75 C	1.95 BC	2.08 B
Drainage water N concentration (mg L^{-1})	39.7 D	88.4 A	79.2 B	58.9 C	76.1 B
Drainage water P concentration (mg L^{-1})	11.2 C	19.4 A	14.6 B	6.7 D	13.4 BC
Total N supply (kg ha^{-1})	401.3 A	367.0 B	254.0 D	297.0 C	301.2 C
Estimated total N leaching (kg ha^{-1})	153.5 B	247.7 A	38.0 E	62.7 D	95.7 C
Total P supply (kg ha^{-1})	112.3 A	91.2 B	67.5 D	81.2 C	84.2 C
Estimated total P leaching (kg ha^{-1})	43.5 B	54.5 A	7.0 D	7.1 D	16.9 C
Mean daily crop ET (mm day^{-1})	1.76 A	1.49 B	1.83 A	1.86 A	1.73 A
Plant height (m plant^{-1})	0.72 A	0.63 B	0.72 A	0.77 A	0.68 A
Leaf area index (dimensionless)	2.65 B	2.35 C	2.89 A	2.91 A	2.65 B
Shoot dry mass (t ha^{-1})	6.00 A	5.00 B	6.20 A	6.50 A	5.90 A
Leaf damage (%)	0 C	64.1 A	0.0 C	0.0 C	42.0 B

*In each row, mean values (n = 4) followed by the same letters are not significantly different ($P < 0.01$) according to LSD test.

Table 6. Influence of irrigation treatments on the balance of water, nitrogen and phosphorus, mean daily crop evapotranspiration (ET) and growth of *Prunus laurocerasus* plants grown in container in Pistoia (Italy) in **2010 (Experiment 3)**. The electrical conductivity (EC) of irrigation water, drainage water and substrate pore water (EC_{PW}), and the leaching fraction are also shown. Plants were watered using different water sources: fresh water (FW), saline water (SW) or a mixture of them (MW) in different ratio according to the level of substrate salinity build-up. Irrigation was automatically scheduled using a pre-set program (TIMER) or a weather-based ET model (MODEL). In two treatments, root zone salinity was controlled based on EC_{PW} measured with a dielectric sensor (MW-MODEL-EC_{PW}) or EC_{DW} measured with a EC probe (MW-MODEL-EC_{DW}). Crop ET was also gravimetrically measured on different dates during the growing season while growth parameters were measured at the end of the experiment. See text for details.

Parameter	**FW-TIMER**	**FW-MODEL**	**SW-MODEL**	**MW-MODEL-EC_{PW}**	**MW-MODEL-EC_{DW}**
Total irrigation water use (IWU; mm)	256.0 A	188.4 C	186.5 C	250.7 AB	239.9 B
Fresh water use (% of IWU)	100 A	100 A	0 D	48.8 B	34.5 C
Water runoff (mm)	85.8 A	23.1 D	26.5 D	78.6 B	72.2 C
Leaching fraction (%)	33.52 A	12.26 B	14.21 B	31.36 A	30.09 A
Irrigation water EC (dS m^{-1})	0.80 C	0.79 C	1.80 A	1.39 B	1.52 B
Drainage water EC (dS m^{-1})	0.91 D	1.01 D	2.36 A	1.94 B	1.73 C
Drainage water N concentration (mg L^{-1})	61.1 B	94.8 A	86.4 A	55.3 B	58.3 B
Total N supply (kg ha^{-1})	222.6 A	190.1 C	194.9 C	207.8 B	210.2 B
Estimated total N leaching (kg ha^{-1})	52.4 A	21.9 C	22.9 C	43.5 B	42.1 B
Mean daily crop ET (mm day^{-1})	1.65 A	1.60 A	1.55 A	1.67 A	1.63 A
Plant height (m $plant^{-1}$)	0.55 A	0.53 A	0.52 A	0.56 A	0.51 A
Leaf area index (dimensionless)	1.10 A	1.15 A	1.17 A	1.12 A	1.15 A
Shoot dry mass (t ha^{-1})	3.40 A	3.10 A	2.70 B	3.20 A	3.20 A
Leaf damage (%)	6.6 C	7.9 C	72.8 A	25.7 B	22.7 B

*In each row, mean values (n = 4) followed by the same letters are not significantly different ($P < 0.01$) according to LSD test.

Table 7. Influence of irrigation treatments on the balance of water, nitrogen and phosphorus, mean daily crop evapotranspiration (ET) and growth of *Photinia x fraseri* plants grown in container in Pistoia (Italy) in **2010 (Experiment 3)**. The electrical conductivity (EC) of irrigation water, drainage water (EC_{DW}) and substrate pore water (EC_{PW}), and the leaching fraction are also shown. Plants were watered using different water sources: fresh water (FW), saline water (SW) or a mixture of them (MW) in different ratio according to the level of substrate salinity build-up. Irrigation was automatically scheduled using a pre-set program (TIMER) or a weather-based ET model (MODEL). In two treatments, root zone salinity was controlled based on based on EC_{PW} measured with a dielectric sensor (MW-MODEL-EC_{PW}) or EC_{DW} measured with a EC probe (MW-MODEL-EC_{DW}). Crop ET was also gravimetrically measured on different dates during the growing season while growth parameters were measured at the end of the experiment. See text for details.

Parameter	**FW-TIMER**	**FW-MODEL**	**SW-MODEL**	**MW-MODEL-EC_{PW}**	**MW-MODEL-EC_{DW}**
Total irrigation water use (IWU; mm)	397.0 A	298.0 D	300.0 D	368.6 B	352.8 C
Fresh water use (% of WU)	100 A	100 A	0 D	48.8 B	26.9 C
Water runoff (mm)	145.7 A	55.9 D	56.8 D	114.4 B	104.5 C
Leaching fraction (%)	36.70 A	18.76 C	18.93 C	31.03 B	29.61 B
Irrigation water EC (dS m^{-1})	0.78 C	0.79 C	1.78 A	1.41 B	1.58 B
Drainage water EC (dS m^{-1})	0.94 C	1.04 C	2.48 A	1.93 B	2.17 B
Drainage water N concentration (mg L^{-1})	42.07 C	51.34 B	61.27 A	40.75 C	42.69 C
Total N supply (kg ha^{-1})	278.5 A	239.5 C	240.1 C	261.5 B	256.3 B
Estimated total N leaching (kg ha^{-1})	61.3 A	28.7 C	34.8 C	46.6 B	44.6 B
Mean daily crop ET (mm day^{-1})	2.12 AB	2.15 A	2.02 B	2.07 B	2.05 B
Plant height (m $plant^{-1}$)	1.03 A	1.05 A	0.95 B	0.99 AB	0.97 AB
Leaf area index (dimensionless)	2.65 AB	2.71 A	2.40 C	2.52 BC	2.50 BC
Shoot dry mass (t ha^{-1})	8.50 A	8.40 A	7.40 B	8.50 A	8.30 A

*In each row, mean values (n = 4) followed by the same letters are not significantly different ($P < 0.01$) according to LSD test.

FIGURE

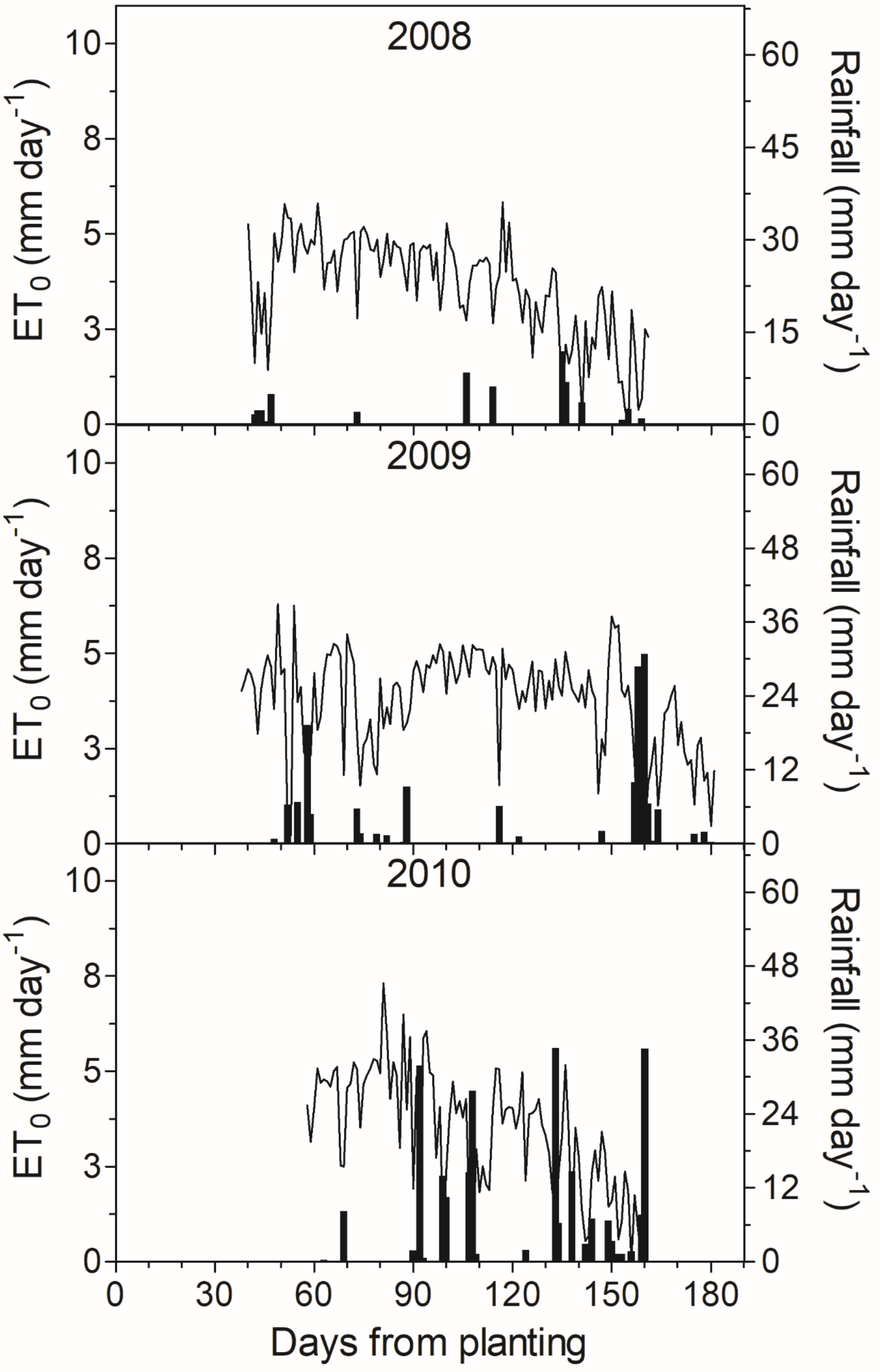
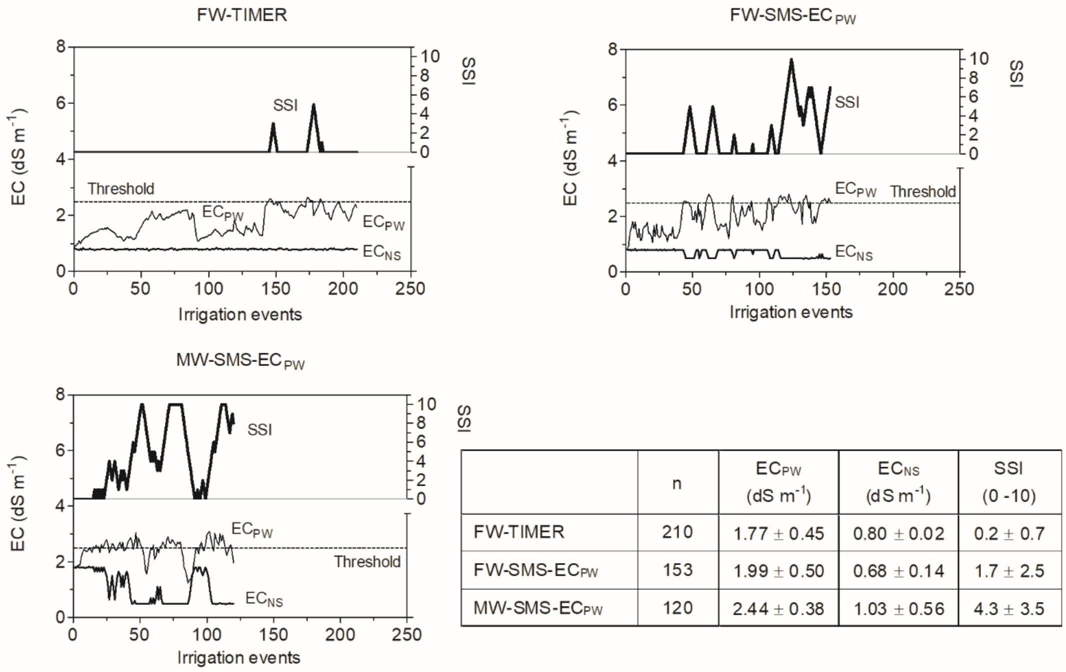
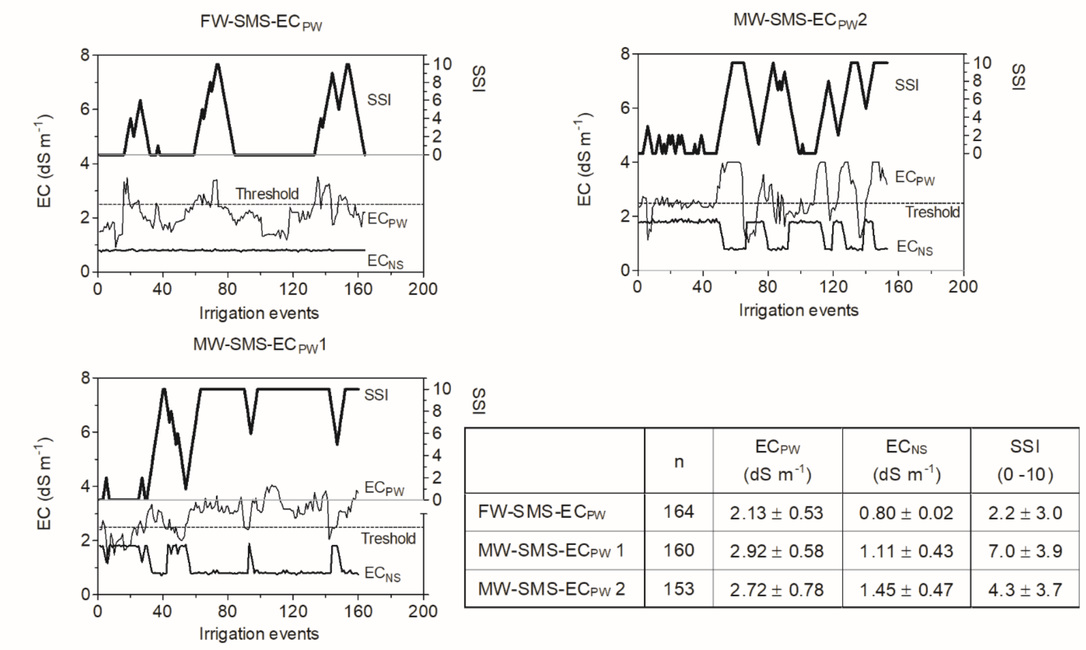


Fig. 1. Mean daily values of reference evapotranspiration (ET$_0$; line) and rainfall (columns) during the experiments conducted with container hardy ornamental nursery crops in Pistoia (Italy) between 2008 and 2010.



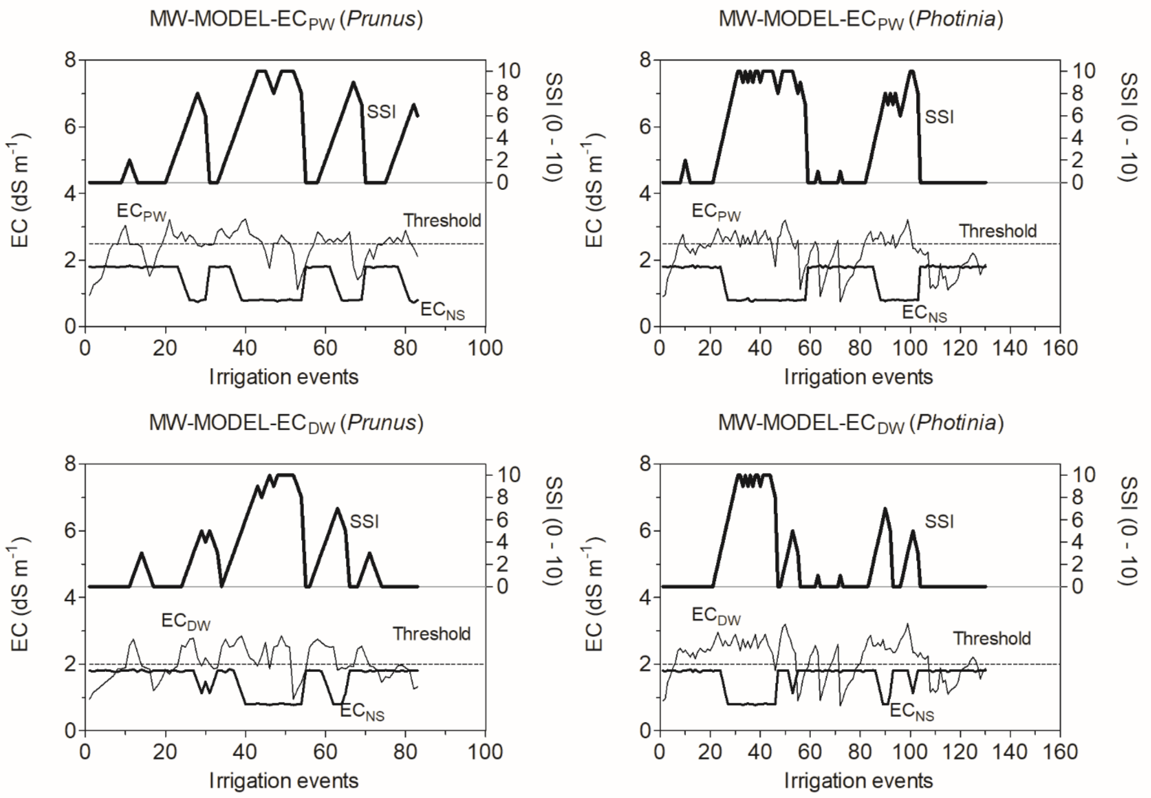
	n	ECPW (dS m-1)	ECNS (dS m-1)	SSI (0 -10)
FW-TIMER	210	1.77 ± 0.45	0.80 ± 0.02	0.2 ± 0.7
FW-SMS-ECPW	153	1.99 ± 0.50	0.68 ± 0.14	1.7 ± 2.5
MW-SMS-ECPW	120	2.44 ± 0.38	1.03 ± 0.56	4.3 ± 3.5

Fig. 2. Influence of irrigation treatments on the electrical conductivity of substrate pore water (EC_{PW}), drainage water (EC_{DW}) and nutrient solution (EC_{NS}), and the salinity stress index (SSI) in *Prunus laurocerasus* plants grown in container in Pistoia (Italy) in **2008 (Experiment 1)**. Plants were watered using different water sources: fresh water (FW) or saline water (SW) or a mixture of them (MW). Irrigation was automatically scheduled using a pre-set program (TIMER) or a WET^{TM} sensor. The SSI is the number of consecutive times that EC_{PW} exceeded the threshold (2.5 dS m^{-1}).



	n	EC$_{PW}$ (dS m^{-1})	EC$_{NS}$ (dS m^{-1})	SSI (0 -10)
FW-SMS-EC$_{PW}$	164	2.13 ± 0.53	0.80 ± 0.02	2.2 ± 3.0
MW-SMS-EC$_{PW}$ 1	160	2.92 ± 0.58	1.11 ± 0.43	7.0 ± 3.9
MW-SMS-EC$_{PW}$ 2	153	2.72 ± 0.78	1.45 ± 0.47	4.3 ± 3.7

Fig. 3. Influence of irrigation treatments on the electrical conductivity of substrate pore water (EC$_{PW}$), drainage water (EC$_{DW}$), nutrient solution (EC$_{NS}$), and the salinity stress index (SSI) in *Prunus laurocerasus* plants grown in container in Pistoia (Italy) in **2009 (Experiment 2)**. Plants were watered using different water sources: fresh water (FW), saline water or a mixture of them (MW). Irrigation was automatically scheduled using a pre-set program (TIMER) or a dielectric sensor (SMS), which also measured EC$_{PW}$, measured with a WET. The SSI is the number of consecutive times that EC$_{PW}$ exceeded the pre-set threshold (2.5 dS m^{-1}).



	EC$_{PW}$ (dS m^{-1})	EC$_{NS}$ (dS m^{-1})	SSI (0-10)	EC$_{PW}$ (dS m^{-1})	EC$_{NS}$ (dS m^{-1})	SSI (0 -10)
	Prunus (83 values)			*Photinia (130 values)*		
MW-MODEL-EC$_{PW}$	2.40 ± 0.05	1.39 ± 0.05	3.7 ± 0.4	2.20± 0.05	1.41 ± 0.42	3.5 ± 0.4
MW-MODEL-EC$_{DW}$	2.04 ± 0.05	1.52 ± 0.05	2.8 ± 0.3	1.96± 0.04	1.58 ± 0.04	2.2 ± 0.3

Fig. 4. Influence of irrigation treatments on the electrical conductivity of substrate pore water (EC$_{PW}$) or drainage water (EC$_{DW}$), nutrient solution (EC$_{NS}$), and the salinity stress index (SSI) in *Prunus laurocerasus* and *Photinia x fraseri* plants grown in container in Pistoia (Italy) in **2010 (Experiment 3)**. Plants were watered using different water sources: fresh water, saline water or a mixture of them in different ratio (MW) according to the level of substrate salinity build-up. Irrigation was automatically scheduled using a weather-based ET model and substrate salinity build-up was controlled based on EC readings of a dielectric sensor or an EC probe. See text for details. The SSI is the number of consecutive times that EC$_{PW}$ or EC$_{DW}$ exceeded a threshold of 2.5 or 2.0 dS m^{-1}, respectively.