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Application of WET Sensor for Management of Reclaimed Wastewater Irrigation in Container-Grown Ornamentals (*Prunus laurocerasus* L.)

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ABSTRACT

The availability of soil moisture sensors (SMS; e.g. WET from Delta-T Devices, UK, and 5TE from Decagon Devices, USA) that are also capable to monitor soil salinity has opened new possibilities for the automatic control of fertigation and the application of a reclaimed wastewater (RW) irrigation scheme in horticultural crops, in particular in container cultivation. In the FLOWAID project, we developed an automated fertigation device that was able to modulate both the irrigation regime and the electrical conductivity (EC) of the nutrient solution (EC_{NS}) based on the measurements of the volumetric water content (θ) and the pore water EC (EC_{PW}) of the growing medium by means of the WET sensor. The prototype was tested in semi-commercial, free-drain container cultivations of cherry laurel (*Prunus laurocerasus* L., a woody ornamental species that is very sensitive to salinity) by simulating the availability of RW (EC = 1.50 dS m^{-1}). RW was prepared by adding NaCl (10 mol m^{-3}) to groundwater (GW; EC = 0.50 dS m^{-1}). Different irrigation treatments, which were differentiated by the method adopted for irrigation scheduling (WET or timer), the source of water (RW and/or GW) and the strategy to avoid an excessive salinization of the growing medium, were compared. The WET sensor activated the irrigation whenever θ dropped to 0.52 m^3 m^{-3} and modulated the EC_{NS} by changing the sources of water (RW or GW) and/or the irrigation dose in order to maintain EC_{PW} below 2.5 dS m^{-1}. The use of the WET sensor reduced markedly the seasonal water use and run-off and the associated leaching of nitrogen and phosphorus with no or reduced effects on plant growth and commercial value, which instead were reduced by the timer-controlled irrigation with the sole RW. This work confirmed that the application of SMS, such as the WET sensor, can improve significantly the water use efficiency in container ornamentals and mitigate the negative effects of RW irrigation in salt-sensitive crops.

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INTRODUCTION

In Italy the production of ornamental nursery stocks is an important horticultural segment, especially in Pistoia (Tuscany) province, where cultivation in containers is increasingly used (Lubello et al., 2004; Pardossi et al., 2004). In commercial nurseries the dosage of water and nutrients is often in excess with respect to the crops' requirements, thus resulting in waste of water and fertilisers that may contribute to the contamination of water bodies with nitrogen (N), phosphorus (P) and other agrochemicals (e.g., herbicides) (Pardossi et al., 2009a). Seasonal irrigation volumes range from 1000 m^3 ha^{-1} in field-cultivated crops to 10,000-15,000 m^3 ha^{-1} in container cultivation. The latter is increasingly popular due to its advantages in terms of cultivation and commercialisation (Pardossi et al., 2004; Pardossi et al., 2009a). In Pistoia, for instance, nearly 1,400 ha, out of approx. 4,500 ha of nurseries, are used for container ornamentals with an estimated yearly consumption of irrigation water (mostly groundwater, GW) of more than 12 million m^3 (Lubello et al, 2004).

Efficient irrigation management in container crops entails the use of substrate moisture sensor (SMS) to regulate the frequency and the rate of water application (Pardossi et al., 2009a, 2009b). Reclaimed municipal or industrial wastewater (RW) represents a source of irrigation water alternative to GW. Many studies demonstrated the possibility of large-scale using RW (Hamilton et al., 2007), also in plant nurseries (e.g. Fitzpatrick et al., 1986; Gori et al., 2000; Lubello et al., 2004). In Pistoia a project is underway for a nurseries irrigation network using the RW from the city, which has an electrical conductivity (EC) ranging from 1.2 to 1.8 dS m^{-1}. Generally, RW has a low quality (Hamilton et al., 2007) and one of the main potential risks of RW reuse in agriculture is the salinity stress induced in sensitive crops, such as many ornamental species (e.g. Fitzpatrick et al., 1986; Wu et al., 1995; Gori et al., 2000).

The availability of SMS (e.g. WET from Delta-T Devices, UK, and 5TE from Decagon Devices, USA) that are also capable to monitor the salinity (namely, electrical conductivity, EC) of the growing medium (soil or artificial substrate) has opened new possibilities for the automatic control of fertigation and the application of a RW irrigation scheme in horticultural crops, in particular in container cultivation (Pardossi et al., 2009b). However, we are not aware of papers on the use of SMS like WET for modulating both the irrigation dose and the salinity of the fertigation water in container crops, apart from the work conducted by Stanghellini et al. (2003) with pepper plants grown in rockwool slabs under greenhouse conditions.

In the FLOWAID project, we developed an automated fertigation device that was able to modulate both the irrigation regime and the EC of the nutrient solution (EC_{NS}) based on the measurements of the volumetric water content (θ) and the pore water EC (EC_{PW}) of the growing medium by means of the WET sensor. The prototype was tested in semi-commercial, free-drain (open-loop) container cultivations of cherry laurel (*Prunus laurocerasus* L., a woody ornamental species that is very sensitive to salinity) by simulating the availability of RW with an EC of 1.50 dS m^{-1}. Five irrigation treatments, which were differentiated by the method adopted for irrigation scheduling (WET or timer), the source of water (RW and/or GW) and the strategy to avoid an harmful salinization of the growing medium, were compared.

MATERIALS AND METHODS

The paper reports the results of an experiment conducted during the spring-summer season of 2009 at the Centro Sperimentale Vivaismo (CESPEVI), Pistoia (Italy). A preliminary trial was out in 2008 with similar results.

Different irrigation treatments were compared using cherry laurel plants cultivated in (24-cm diameter) plastic pots at a density of 2.4 pot m^2. The cultivation started on 27 April 2009 and the observations started five weeks later and ended in October (130 days). Two 'spaghetti' drippers with a discharge rate of 6.0 L/h were placed in each pot containing approx. 8.5 L of a peat-pumice mixture (1:1, v/v), which had been enriched with controlled-release fertilizer (5.0 kg m^{-3}; 18-9-10 NPK). The amounts of N and P contained in the fertilisers incorporated in the substrate prior to planting were, respectively, 183.6 and 40.1 kg ha^{-1}.

Two sources of irrigation water were tested: GW (EC_{IW} = 0.5 dS m^{-1}) and RW (EC_{IW} = 1.5 dS m^{-1}). RW was prepared by adding 10 mol m^{-3} NaCl to GW. During the cultivation, the fertigation device prepared the nutrient solution by adding a soluble fertilizer (18-11-18 NPK) to the raw water (GW, RW or a mixture of them) at a concentration of 0.25 kg m^{-3}, which resulted in an *EC* increase of 0.30 dS m^{-1} and adjusting the pH to 6.0 by means of small quantities of diluted sulphuric acid.. GW contained 0.11 mol m^{-3} of P (phosphate) and negligible N (nitrate and ammonium) content; therefore, the concentrations of N, P and K in the nutrient solution were 3.21, 0.50 and 0.96 mol m^{-3}, respectively. EC and pH probes were calibrated every two or three weeks.

The irrigation was regulated by a fertigation system developed from an existing commercial device (MCi 300, Spagnol Greenhouse Technologies, Vidor, Italy) by connecting three WET sensors and implementing appropriate algorithms in the control software. The system could be monitored and operated by a personal computer, also remotely through the Internet.

WET is a dielectric sensor that measures permittivity (ε), bulk electrical conductivity (EC_B) and temperature simultaneously in the same soil volume (Balendonck and Hilhorst., 2001). EC_B and ε were converted to EC_{PW} or to θ by means of specific calibrations for the peat-pumice mixture (Incrocci et al, 2009).

Five irrigation treatments were compared. In TiGW and TiRW the irrigation (with GW and RW, respectively) was controlled by a simple timer. The pots were watered initially once per day till the end of June, subsequently twice per day. Irrigation dose ranged from 1.50 to 3.26 L m^{-2} during the season following the instructions from a local grower, which represented the standard management criteria in commercial nurseries in Pistoia. The expected leaching fraction (LF; the ratio between drainage and irrigation water) was >40%.

In the other treatments (WETGW, WETRW1, WETRW2), the fertigation was regulated by the WET sensor. In each plot, one sensor was inserted vertically into the reference pot (sentinel) with the three (7 cm-long) pins positioned approx. between 4 and 11 cm from the top surface and between 3.5 and 5 cm from the pot wall.

The WET-based control system aimed to reduce the consumption of GW, also by using RW (WETRW1 and WETRW2) and to prevent the excessive salinization of the growing medium. The irrigation was initiated whenever θ was lower than 0.52 m^3 m^{-3}, which corresponded to a matric potential of approximately -4.5 kPa, as determined at the beginning of the growing season with an hydraulic tensiometer (SWT4, Delta-T Devices, Burwell, UK) buried in the same pot close to the WET measuring zone. The standard watering dose was 0.96 L pot^{-1} (2.30 L m^{-2}). θ oscillated between 0.52 and 0.62 m^3 m^{-3} in the sentinel pot. This oscillation corresponded to approximately 0.80 L pot^{-} on the basis the relationship between the θ of the whole pot and in the WET measuring zone, which was determined in a preliminary experiment. Therefore, the expected LF was around 17%. Moreover, a salinity stress index (SSI) was computed by comparing the EC_{PW} readings to a threshold of 2.5 dS m^{-1}, which was defined in a previous experiment as the maximum tolerable salinity level for the crop under investigation. Default value for SSI was zero.

Whenever EC_{PW} exceeded 2.5 dS m^{-1}, SSI increased by one unit with a maximum value of 10. On the contrary, SSI decreased by one unit when EC_{PW} remained below 2.5 dS m^{-1} (evidently only for SSI values higher than 0); if two consecutive EC_{PW} readings were lower than the threshold, SSI was reset to zero. Two different measures were adopted to prevent the substrate salinization: 1) the standard water gift of 0.8 L pot^{-1} was augmented, thus increasing LF; 2) EC_{IW} was modulated by varying the RW:GW mixing ratio (only in WETRW1 and WETRW2). In each WET treatment, a different strategy was designed by setting up, for any potential value of SSI, the irrigation dose, EC_{IW} and then EC_{NS} (Table 1). In order to avoid the influence of θ on the EC_B vs. EC_{PW} relationship (Regalado et al., 2007; Incrocci et al., 2009), the controller used only the WET readings at full container water capacity, which is a relatively constant quantity, since it depends on the substrate water retention curve and the container geometry. As a matter of fact, only the readings taken 10 min after irrigation, when free drainage had terminated, were used by the software for computing SSI.

During the growing season, approx. every two weeks (17 days in total), along with the plant height the daily water (including evapotranspiration, ET) and nutrient balance sheets for single pots in each treatment were determined by measuring the volume, pH, the EC and macronutrient concentration of supplied and drainage nutrient solution (these quantities were then used to compute LF) as well as the daily change in pot weight (in order to take into account the possible variation in θ).

Table 1. Water source (i.e., the ratio between groundwater, GW, and reclaimed wastewater, RW, in the irrigation water), the EC of irrigation water (EC_{IW}) or nutrient solution (EC_{NS}), irrigation dose and expected leaching fraction (LF) in the WET-based irrigation treatments (WETGW, WETRW1, WETRW2) as a function of root zone stress index (SSI). SSI was computed by comparing the WET measurements of EC_{PW} to a threshold of 2.5 dS m^{-1}. See text for the meaning of abbreviations.

SSI	Water source (GW:RW)	EC_{IW} (dS m^{-1})	EC_{NS} (dS m^{-1})	Irrigation dose (L/m^2)	LF
			WETGW		
0	100:0	0.50	0.80	2.30	0.17
1	100:0	0.50	0.80	2.55	0.25
2	100:0	0.50	0.80	2.80	0.32
3	100:0	0.50	0.80	3.05	0.37
4	100:0	0.50	0.80	3.30	0.42
5	100:0	0.50	0.80	3.55	0.46
6 ÷ 10	100:0	0.50	0.80	3.80	0.50
			WETRW1		
0	0:100	1.50	1.80	2.30	0.17
1	33:67	1.20	1.50	2.30	0.17
2	67:33	0.90	1.20	2.30	0.17
3	100:0	0.50	0.80	2.30	0.17
4	100:0	0.50	0.80	2.80	0.32
5	100:0	0.50	0.80	3.20	0.40
6 ÷ 10	100:0	0.50	0.80	3.80	0.50
			WETRW2		
0	0:100	1.50	1.80	2.30	0.17
1	0:100	1.50	1.80	2.80	0.32
2	0:100	1.50	1.80	3.20	0.40
3	0:100	1.50	1.80	3.80	0.50
4	33:67	1.20	1.50	3.80	0.50
5	67:33	0.90	1.20	3.80	0.50
6 ÷ 10	100:0	0.50	0.80	3.80	0.50

Single water application in each plot were automatically recorded by the prototype while the daily water drainage (run-off) was calculated as the measured irrigation volume times the LF expected for each day on the basis of the periodical determinations of pot water balance (explicitly, for a given period between two consecutive samplings, the mean of the values determined at the beginning and at the end of the period was used). Total water use and run-off were computed by the sum of the daily values for irrigation and drainage volume, respectively. The balance sheets for N and P was derived from the amount of slow-release fertiliser added to the substrate and from the total supply of nutrients by fertigation, which in turn was calculated as the product of the seasonal volume of irrigation water and its nutrient concentration. Nutrient leaching was determined by accumulating the daily nutrient loss with drainage water, which was computed as the product of the daily drainage volume and its ion concentration expected for each day, likewise LF. At the end of growing season, plant height, leaf area index and shoot dry mass were measured in four individuals in each plot. Since visual appearance is crucial in ornamental plants, the extent of foliar damage (leaf burn) due to the salinity was also assessed by determining the percentage of damaged leaves in 16 plants per treatment. The influence of irrigation treatment on some parameters was assessed by means of ANOVA and LSD test.

RESULTS

The prototype worked adequately and the strategies adopted in the WET treatments were applied correctly. Moreover, in all plots the plants grew uniformly, as also demonstrated by the low variability of the experimental determinations (data not shown), and in the irrigation plots controlled by the WET sensor the sentinel plants appeared to represent adequately the performance of the whole batch of plants in terms of growth and ET.

The irrigation regime did not influence significantly crop ET (Table 2). The season-average water gift was 1.07, 0.95, 0.84, 1.06 and 1.14 L pot^{-1} in TiGW, TiRW, WETGW, WETRW1 and WETRW2, respectively. In TiGW and TiRW, LF averaged 0.56 and this value is in the typical range (0.30-0.60) dictated by the common management practice in commercial nurseries in the area of Pistoia. Compared to timer-based regimes, the application of the WET sensor reduced both the LF and the frequency of irrigation, since the number of irrigations was reduced roughly by one third; as a consequence, the seasonal water use and run-off were markedly diminished (by 35% and 72%, respectively). On average, total water use was 4,678 m^3 ha^{-1}. RW contributed to the total water use by 14% in WETRW1 and by 44% in WETRW2.

In WETRW1 and WETRW2, EC_{NS} averaged 1.11 ± 0.42 dS m^{-1} (±SD; n = 157) and 1.47 ± 0.47 dS m^{-1} (n = 153), respectively. Compared to GW irrigation, the use of RW resulted in higher EC and nutrient concentration of the drainage water only when the irrigation was controlled by timer (Table 2). There were no important differences in these parameters among WETGW, WETRW1 and WETRW2.

During the season, the oscillations in EC_{PW} were more pronounced in WETRW2 than in WETRW1 (data not shown). In the sentinel pot of WETGW, EC$_{PW}$ exceeded rarely the threshold of 2.5 dS m^{-1} (with a maximum value of 3.51 dS m^{-1}) and averaged 2.13 ± 0.54 dS m^{-1} (n = 163). Conversely, in WETRW1 EC$_{PW}$ remained 0.5-1.2 dS m^{-1} above the threshold (apart from the first weeks of observations) with an average of 2.91 ± 0.60 dS m^{-1} (n = 159), whereas it fluctuated markedly in WETRW2 reaching values higher than 5.5 dS m^{-1} in several occasions (the mean was 2.85 ± 10.3 dS m^{-1}, n = 149).

Table 2. The influence of irrigation treatment on daily crop evapotranspiration (ET), leaching fraction (LF), the electrical conductivity (EC) and the nitrogen (N; nitrate plus ammonium) or phosphorus (P; phosphate) concentrations of the drainage water, the number of water applications, the balance sheet for water, N and P, and plant growth in container-grown plants of *Prunus laurocerasus*. For ET, LF and the EC and nutrient concentration of the drainage water, the mean values of three replicates are shown; different letters denote statistical significance according to LSD test (P<0.05). See text for the meaning of abbreviations.

	TiGW	TiDW	WETGW	WETRW1	WETRW2
Daily crop evapotranspiration (ET; m^3 ha^{-1})	15.6 a	14.9	18.3 a	18.7 a	17.3 a
Leaching fraction (LF)	0.52 a	0.50 a	0.14 c	0.26 b	0.30 b
Drainage water EC (dS m^{-1})	1.19c	2.80	1.75b	1.95	2.08
Drainage water N concentration (mol m^{-3})	3.10 c	6.15 ab	6.20 a	6.14 ab	5.68 b
Drainage water P concentration (mol m^{-3})	0.35 c	0.63 a	0.35 c	0.48 b	0.52 b
Irrigation events	242	244	162	157	153
Total water use (m^3 ha^{-1})	6223	5579	3389	4014	4182
Total drainage water (m^3 ha^{-1})	3868	2803	480	1064	1258
Total N supply (kg ha^{-1})	463.4	434.4	336.0	364.1	371.6
Estimated total N leaching (kg ha^{-1})	153.5	247.7	38.0	62.7	95.7
Total P supply (kg ha^{-1})	136.6	126.6	92.6	102.6	104.9
Estimated total P leaching (kg ha^{-1})	43.5	54.5	7.0	7.1	16.9
Plant height (m plant^{-1})	0.72 a	0.63 a	0.72 a	0.77 a	0.68 a
Leaf area index (dimensionless)	2.65 a	2.35 a	2.89 a	2.91 a	2.65 a
Shoot dry mass (t ha^{-1})	6.0 a	5.0 b	6.2 a	6.5 a	5.9 a

The fertigation regime affected the balance sheets for N and P (Table 2). The application of the WET sensor reduced considerably the amount of these nutrients supplied to the crop by fertigation (N, -35%; P, -35%) or leached out (N, -67%; P, -79%) during the whole growing season. In TiGW, TiRW, WETGW, WETRW1 and WETRW2 the apparent nutrient uptake (computed as the difference between the supply and the leaching) was, respectively, 309.9, 186.7, 298.0, 301.4 and 275.9 kg ha^{-1} for N, and 93.1, 72.1, 85.6, 95.5 and 88.0 kg ha^{-1} for P.

No significant effect of fertigation regime on plant growth was observed apart from a significant reduction in shoot dry mass of TiRW plants (Table 2). The number of damaged leaves was negligible in TiGW, WETGW and WETRW1; however, it accounted for 64.1 % and 42.0 % in TiRW and WETRW2, respectively.

DISCUSSION

Several authors demonstrated that the application of SMS in irrigation scheduling may reduce significantly the water use in nursery and greenhouse crops without any important effects on crop productivity (Pardossi et al., 2009b). In our experiment, the use of the WET sensor reduced by 35% the water application compared to timer scheduling with a positive effect also in terms of nutrient leaching (Table 2) in agreement with previous work conducted in similar conditions (Pardossi et al., 2009a). Water saving in the WET treatments resulted from a reduction in the frequency of watering associated to a lower LF for each water gift (especially in WETGW). In these treatments the substrate dehydrated more than in the timer-controlled irrigation sectors and this increased the amount of water retained the pots when they were watered.

The fertigation system also modulated the salinity of the fertigation water based on the measurement of EC_{PW}. In point of fact, only in WETGW the EC_{PW} was maintained lower than the threshold, whereas in WETRW1 and WETRW2 EC_{PW} remained higher notwithstanding the continuous modulation of both irrigation dose and EC_{NS}. However, both strategies reduced significantly the negative effects that were observed when the RW was the sole source of irrigation water (TiRW). Apparently, the higher foliar damage occurring in WETRW2 than in WETRW1 were accounted for by the larger oscillations in the substrate salinity, since no important differences were observed between these treatments in the mean values of the EC of drainage solution (EC_{DW}) and EC_{PW}. In a parallel experiment conducted to test the same irrigation treatments on other woody ornamental species (such as *Photinia x fraseri, Viburnum tinus,* and *Forsythia intermedia*), which are more tolerant to salinity than cherry laurel, similar results were found as regards the water and nutrient balance without any significant effects on plant growth and commercial value (L. Incrocci, unpublished results).

RECOMMENDATIONS

For the WET sensor, a substrate specific calibration is necessary for converting ε to θ and EC_B to EC_{PW} (Balendonck et al., 2004; Incrocci et al., 2009). Moreover, to overcome the possible effect of θ on the relationship between EC_B to EC_{PW} (Regalado et al., 2007; Incrocci et al., 2009), an expedient is to use only the readings taken at the same θ, as a matter of fact soon after each water application, when the substrate is at or very close to the water container capacity.

In our trials, the performance of the fertigation system, including the consistency of the WET readings in the sentinel pot, were checked daily, also through the Internet. This made it possible to install one WET sensor only in each plot. However, in commercial cultivations at least two sensors are necessary for each irrigation sector along with a set of safety instructions integrated in the control software (e.g. minimum and maximum duration of watering, maximum elapsed time without irrigation etc.) in consideration of possible sensor failure and/or the divergence in water requirements (namely, ET) between the monitored plant(s) and those not monitored.

Moreover, since generally RW contains significant quantities of nutrients (e.g., Gori et al., 2000; Lubello et al., 2004), the nutrient concentration of the fertigation water determined by the addition of soluble fertilisers should be modulated as a function of the RW composition and its fraction in the raw water used by the fertigator. Indeed, a specific instruction in this sense was integrated in the software of the fertigation system and included in the control strategy for the RW irrigation tested in the experiment conducted in 2008.

CONCLUSIONS

This work confirmed that the application of SMS, such as the WET sensor, can improve significantly the water use efficiency in container ornamentals, also by regulating the salinity of the irrigation/fertigation water. These sensor can be easily interfaced to commercial irrigation controllers, although some specific algorithms have to be implemented in the control software, such as those necessary to compute the SSI that determines the set-points for the relevant fertigation parameters.

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