doi: 10.17221/312/2014-HORTSCI

Timer versus moisture sensor-based irrigation control of soilless lettuce: Effects on yield, quality and water use efficiency

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Abstract

Montesano F.F., van Iersel M.W., Parente A. (2016): **Timer versus moisture sensor-based irrigation control of soilless lettuce: Effects on yield, quality and water use efficiency**. Hort. Sci. (Prague), 43: 67–75.

The study compares the effects of: timer ('Timer') and soil moisture sensor-controlled irrigation on soilless lettuce; two volumetric water content (Θ) thresholds for irrigation (0.30 ('Θ = 0.3') and 0.40 m^3/m^3 ('Θ = 0.4')). The most nutrient solution (NS) was applied in 'Timer' where the lowest water use efficiency was observed, with 17 and 42% less NS used in 'Θ = 0.4' and 'Θ = 0.3', respectively. Irrigation volumes followed the plant water needs in the sensor-controlled treatments, with little or no leaching, while 18% of leaching was recorded in 'Timer'. Plants in 'Timer' and 'Θ = 0.4' had higher fresh weights (24%) and leaf area (13%) than plants in 'Θ = 0.3'. Similar dry weight was observed among treatments but percentage of dry matter was 20% higher in 'Θ = 0.3'. Gas exchanges and leaf tissues chemical composition were similar in all treatments, but nitrate concentration was lower in the 'Θ = 0.3' plants. Precision sensor-controlled irrigation based on Θ measurements is an effective tool to increase the overall water use efficiency and to improve the quality of soilless-grown lettuce by acting on the substrate moisture level.

Keywords: *Lactuca sativa* L. var. *capitata*; greenhouse; volumetric water content; leaching; easily available water

Minimally processed or fresh-cut leafy vegetables, such as lettuce (*Lactuca sativa* L.), have been gaining importance in the worldwide vegetable market. Leafy lettuce was traditionally cultivated in soil, but recently soilless cultivation techniques have been considered. There can be large differences between soil and soilless systems in terms of inputs, size, location, environmental conditions and productivity (Selma et al. 2012). Although greenhouse soilless cultivation could be impaired in some regions of the world by the generally high capital investments and energy requirements, greenhouse production of leafy vegetables using soilless culture permits precise control of plant nutrition, and allows for more efficient water and nutrient use and higher sanitary quality than conventional, soil-based culture. Soilless culture can also simplify post-harvest handling and waste-water treatment (Valenzano et al. 2008; Fallovo at al. 2009; Manzocco et al. 2011). Several recent studies focused on the effects of nutrient solution (NS) mineral composition on lettuce yield and quality in soilless cultivation systems (Fallovo et al. 2009; Scuderi et al. 2011). However, there is a general lack of information on

Supported by project "Efficient Irrigation Management Tools for Agricultural Cultivations and Urban Landscapes" (IRMA) – European Territorial Cooperation Programmes (ETCP), Greece-Italy 2007–2013.

doi: 10.17221/312/2014-HORTSCI

the influence of irrigation management on soilless lettuce yield and quality.

Irrigation management directly affects crop performance, and efficient irrigation practices can lead to qualitative and quantitative improvements in vegetable production (Dukes et al. 2010). Efficient irrigation management also contributes to the sustainable use of water. Increasing competition for water resources (Jury, Vaux 2005) has raised consumer and government interest in the environmental impact of food production. As a result of the increasing pressure on limited water resources, member states of the European Union implemented the Water Framework Directive, which aims to assure the good ecological status of all water bodies (Anonymous 2000). Since agriculture is an important source of nonpoint source water pollution, it may be necessary to adopt agricultural practices which minimize the release of pollutants to meet societal goals and satisfy government regulations (Blackstock et al. 2010). For the greenhouse industry, this means that irrigation management will become increasingly important, since excessive irrigation results in low water use efficiency, leaching, and runoff of water, fertilizer, and other agrochemicals.

Irrigation management using timers or the visual assessment of plants and substrate is generally inefficient (Nemali et al. 2007). An alternative approach is to monitor the water status of the soil or substrate and make objective irrigation decisions based on real-time measurements (Jones 2007). Soilless substrates generally hold most of the water in a matric potential range from –1 to –10 kPa, with matric potentials of –1 to –5 kPa accounting for easily available water (EAW) and water occurring between –5 and –10 kPa being considered "water buffering capacity" (WBC) (de Boodt, Verdonck 1972; Argo 1998). Knowledge of water availability in the growing media can be used to determine appropriate thresholds for automated irrigation. Still, little work has been done to correlate the commonly defined EAW or WBC with plant growth (Altland et al. 2010).

Irrigation has been automated using water tension measurements for decades (Shock, Wang 2011), but few growers currently do so, because even "micro"- tensiometers are bulky and require frequent maintenance and refilling. Tensiometers can easily become dislodged from the substrate, breaking capillarity and leading to faulty readings (van Iersel et al. 2013). Substrate volumetric water content (Θ) has recently become a more feasible parameter for determining substrate water status and automating irrigation due to the development of low-cost sensors (Jones 2007; Nemali, van Iersel 2006). By using media-specific water retention curves, it is possible to correlate substrate Θ with matric potential, and use Θ to determine thresholds for precision irrigation.

This study compares the effects of timer- and soil moisture sensor-controlled irrigation on the water use, yield and quality of lettuce grown in soilless substrate. It also compares two different Θ thresholds, which were determined based on the substrate EAW. It was hypothesized that using Θ thresholds to control irrigation would reduce water use, without affecting lettuce yield and quality.

MATERIAL AND METHODS

Plant material and growing conditions. The experiment was carried out in a greenhouse at the experimental farm "La Noria" of the Institute of Sciences of Food Production (CNR - ISPA) in Mola di Bari (Southern Italy). Seedlings of *Lactuca sativa* L. var. *capitata* cv. Mortarella d'Inverno (S.A.I.S. Sementi, Cesena, Italy) were obtained from a commercial nursery and transplanted into 5 l plastic containers (one plant per container) filled with a soilless substrate (peat-perlite, 1:1 v/v). The substrate was saturated with water before transplanting. Initial substrate solution electrical conductivity (EC) was 0.8 dS/m as measured with an *in situ* EC sensor (WET sensor; Delta T Devices, Burwell, U.K.). After transplanting, the seedlings were watered with a nutrient solution (NS) prepared with pre-collected rain water and containing 8mM N-NO_3, 2mM N-NH_4, 5.1mM K, 1.6mM P, 1.2mM Mg, 2.5mM Ca, 2.8mM S, with micronutrients applied according to Johnson et al. (1957). The NS had an EC of 1.5 dS/m and a pH of 6.0. All plants were well-watered using the NS for 8 days after transplanting (DAT) to allow the seedlings to establish. The experiment was terminated at 50 DAT, when plants reached the commercial size typical for the cultivar. Mean temperature and relative humidity inside the greenhouse were 15.6°C and 84.7%, respectively. The mean daily light integral was 7.84 mol/m^2/d during the experiment.

Determination of substrate EAW and irrigation thresholds. Substrate volumetric water con-

doi: 10.17221/312/2014-HORTSCI

tent at –5 kPa (water potential limit for EAW) was measured using a sand-box (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) in accordance with the European Standards EN 13041:1999 (Soil improvers and growing media – Determination of physical properties – Dry bulk density, air volume, shrinkage value and total pore space). The substrate was equilibrated in water, transferred into tubes made of two overlapping PVC rings (100 ± 1 mm diameter and 50 ± 1 mm height each), and saturated with water for 48 hours. The PVC tubes with substrate were then moved to the sandbox and kept at a pressure of –5 kPa at room temperature until they reached a constant weight. The PVC rings were removed from the sandbox and separated, after which the substrate from the lower rings was weighed and dried at 105°C to a constant weight. Based on these measurements, it was determined that the Θ value limit of the EAW was 0.38 m^3/m^3 for this substrate. Two irrigation thresholds were chosen accordingly in order to control substrate Θ at slightly above (0.40 m^3/m^3) and well below (0.30 m^3/m^3) the EAW limit.

Treatments and experimental design. The treatments were: (i) timer-controlled irrigation ('Timer'); (ii) irrigation controlled with soil moisture sensors with a Θ thresholds of 0.40 m^3/m^3 (above the threshold for EAW) ('Θ = 0.4'), and (iii) irrigation controlled with soil moisture sensors with a Θ threshold of 0.30 m^3/m^3 (value lower than the EAW limit) ('Θ = 0.3'). Plants were arranged in a randomized complete block design with three replications. The experimental unit was a set of two plants and containers (subsamples), with one of the two used to monitor Θ and control irrigation, for a total of 18 plants used in this experiment (3 treatments × 3 replications × 2 subsamples).

The control system used to irrigate based on Θ thresholds was similar to that described by Nemali and van Iersel (2006). EC-5 sensors were used rather than EC-10 sensors (Decagon Devices, Pullman, USA), because EC-5 sensors are less sensitive to substrate electrical conductivity (EC) and temperature (Nemali et al. 2007). One sensor was inserted at a ≈ 45° angle into the substrate in each of the 9 measured containers. Sensor voltage output was measured every 20 min using a CR1000 datalogger (Campbell Scientific, Logan, USA) which converted voltage measurements to Θ using a substrate-specific calibration equation (Θ = voltage × 3.3007 – 0.2555, r^2 = 0.99, 2,500 mV sensor excitation voltage). Each replication of the 'Θ = 0.3' and 'Θ = 0.4' treatments had a dedicated pump (Shott 12.10/1400; Shott International, Cittadella, Italy) and EC-5 sensor. Whenever the measured Θ dropped below the threshold value (0.30 or 0.40 m^3/m^3), the datalogger sent a signal to a relay driver (SDM16AC/DC controller; Campbell Scientific, Logan, USA) which turned on the pump to irrigate the 2 containers for 3 minutes. Water was allowed to equilibrate in the substrate for 17 min before the next measurement and potential irrigation event. Pumps were submerged in a 500 l tank filled with NS, and delivered 30 ml/min (90 ml of NS/irrigation event) to each container through two pressure-compensated emitters. In the 'Timer' treatment, Θ was measured but not used for irrigation control. These plants were irrigated once daily (90 ml NS) for 26 DAT and twice a day (180 ml NS) thereafter using a single submerged pump for the 3 replications. This irrigation frequency maintained a leaching fraction of approximately 20%. Leachate from each container in all treatments was collected in buckets, and the volume was measured weekly.

Measurements, calculations and statistical analysis. The data logger stored the Θ readings from all sensors every 20 min, the average of the sensor readings for each measured container every hour, and the daily number of irrigation events for each replication of the sensor-controlled treatments. Daily and total irrigation volumes were calculated based on the number of irrigations recorded and the known volume per irrigation event. Leaf chlorophyll content was measured non-destructively using a handheld leaf chlorophyll meter (SPAD-502; Minolta, Ramsey, USA) at 42 DAT. Measurements were taken on ten well-expanded young leaves per plant, and the averages were recorded for each plant. Leaf net CO_2 assimilation rate (A_n), stomatal conductance to water vapour (g_{sw}) and transpiration (T) were measured at 40 DAT using a portable photosynthesis system (LI-6400; LI-COR Biosciences, Lincoln, USA) which provided a photosynthetic photon flux (PPF) of 1,000 μmol/m^2·s and a CO_2 concentration of 400 μmol/mol. Measured leaves were allowed to adjust to the measurement conditions for at least 20 min before the values were recorded. Plants were harvested, and substrate EC in each container was measured using a WET sensor at 50 DAT. The number of leaves was recorded and the shoot fresh weight of each plant was determined. Total leaf area was measured using a leaf area me-

doi: 10.17221/312/2014-HORTSCI

ter (Li-3100; LI-COR Biosciences, Lincoln, USA). The leaves and stems of each plant were dried in a thermo-ventilated oven at 65°C until they reached a constant weight. Percent dry matter was calculated as [(dry weight/fresh weight) × 100]. Water use efficiency (WUE) was calculated as a function of the applied irrigation water (WUE_a = total dry weight of shoots/irrigation volume applied) and irrigation water without leaching [WUE_r = total dry weight of shoots/(irrigation volume applied – leachate)]. Instantaneous WUE (WUE_i) was calculated from the leaf gas exchange measurements ($WUE_i = A_n/T$).

Dried leaves were finely ground through a mill (IKA; Labortechnik, Staufen, Germany) with a 1.0 mm sieve. Leaf nutrient concentrations were determined using ion chromatography (Dionex DX120; Dionex Corporation, Sunnyvale, USA) and a conductivity detector with the IonPackAG14 pre-column and the IonPack AS14 separation column for anions, and IonPack CG12A pre-column and IonPack CS12A separation column for cations. Inorganic anions were measured using 0.5 g of ground leaf tissue with 50 ml solution containing 3.5mM sodium-carbonate and 1.0mM sodium-bicarbonate. Inorganic cations were measured using 1 g of ground leaf tissue, ashed in a muffle furnace at 550°C and digested with 20 ml 1M HCl in boiling water for 30 min (Elia et al. 1996).

Data were subjected to ANOVA using the general linear model procedure (SAS Institute, Cary, USA); means were separated by LSD test with $P \leq 0.05$ considered to be statistically significant.

RESULTS AND DISCUSSION

Substrate water content, irrigation volume and water use efficiency, substrate EC

Substrate Θ was different in the three treatments. In the 'Timer' treatment, Θ was higher than 0.45 m^3/m^3 for the most of the growing cycle and dropped below this value only during the last part of the cycle (Fig. 1). The sensor-controlled system generally maintained Θ close to the irrigation thresholds despite increases in plant size. The average Θ measured by sensors was 0.461 ± 0.011, 0.412 ± 0.007 and 0.320 ± 0.009 m^3/m^3 (mean ± sd) in the 'Timer', "Θ = 0.4" and "Θ = 0.3" treatments, respectively (for the two sensor controlled treatments, the reported Θ values are calculated starting from the beginning of irrigation controlled by the automated system, after Θ dropped for the first time below the respective irrigation threshold). The 'Θ = 0.3' treatment resulted in greater Θ fluctuations than did the 'Θ = 0.4' treatment (Fig. 1). This is consistent with previous findings (Nemali, van Iersel 2006; van Iersel et al. 2010) and may be because the hydraulic conductivity of peat-based substrates decreases at lower water contents (Naasz et al. 2005), resulting in slower water movement, less uniform water distribution, and increased Θ variability. It took an average of 9 d for the substrate of the 'Θ = 0.4' treatments to reach the irrigation threshold (0.40 m^3/m^3) and 23 days for the 'Θ = 0.3' treatments to reach the 0.30 m^3/m^3 threshold.

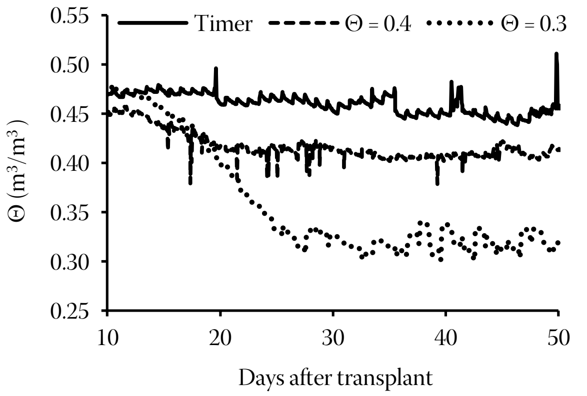

Fig. 1. Average volumetric water content (Θ) readings of soil moisture sensors in pots irrigated with a timer or with an automatic irrigation system based on Θ threshold (0.30 for 'Θ = 0.3' and 0.40 m^3/m^3 for 'Θ = 0.4') measured by substrate moisture sensors

The most irrigation water was applied in the 'Timer' treatment, with 17% less NS used in the 'Θ = 0.4' treatment, and 42% less in the 'Θ = 0.3' treatment (Table 1). Approximately 18% of applied NS leached out from the containers when the timer was used for irrigation control, while little or no leaching occurred in the sensor-controlled treatments (Table 1). Irrigation volumes fluctuated daily in the sensor-controlled treatments due to variability in plant water consumption and the corresponding changes in the rate of substrate water depletion (Fig. 2). Sensor-controlled irrigation reduces the amount of NS applied and effectively eliminates leaching. Using Θ to automate irrigation ensures that NS is provided to the plant only when water is lost from the substrate due to plant consumption or evaporation. Limiting the duration and volume of irrigation events based on container size and substrate water reten-

doi: 10.17221/312/2014-HORTSCI

Table 1. Applied nutrient solution (NS), volume of leachate, water use efficiency (WUE), and substrate electrical conductivity (EC) in soilless cultivation of lettuce where irrigation management was performed with a timer or with an automatic irrigation system based on Θ threshold (0.30 for 'Θ = 0.3' and 0.40 m^3/m^3 for 'Θ = 0.4') measured by substrate moisture sensors

Treatment	Applied NS (ml/plant)	Leachate (ml/plant)	WUE_a [2] (g/l)	WUE_r [3] (g/l)	Substrate EC (dS/m)
Timer	5,310[a]	933[a]	2.36[c]	2.86[b]	1.1[b]
Θ = 0.4	4,410[b]	59[b]	2.95[b]	2.99[b]	1.1[b]
Θ = 0.3	3,060[c]	0[b]	4.02[a]	4.02[a]	1.4[a]
Significance[1]	***	***	***	**	***

[1]mean separation within columns by $LSD_{0.05}$; **, *** – significant at $P \leq 0.01$ and $P \leq 0.001$, respectively; [2]calculated as a function of the applied irrigation water; [3]calculated as a function of the irrigation water retained in the substrate; within columns, values followed by the same letters are not significantly different

tion properties maximizes the efficiency of sensor-controlled irrigation systems. Leaching from soilless substrates can generally be minimized by reducing the duration of each irrigation event, thereby applying less water at one time (Yeager et al. 1997; Burnett, van Iersel 2008). In our experiment, the leaching fraction in the 'Timer' treatment was lower than is typical for soilless production systems, since it is common in substrate systems to apply 30–50% more water than is used by the crop (Kläring 2001), suggesting that the water saving obtained using moisture sensors could even be higher in commercial growing conditions.

Water use efficiency calculated based on the applied irrigation water is a measure of whole system (irrigation and cultivation system combined) efficiency, which takes into account both the actual plant water use and the water lost through leaching. In the 'Timer' treatment, WUE_a was the lowest because of the large volume of NS that was applied, and WUE_a was the highest in the 'Θ = 0.3' treatment, which used the least NS (Table 1). The substantial leaching that generally occurs with timer-based irrigation decreases its WUE_a. Reducing leaching during production by growing plants at the optimal substrate water content and growing species with high water-use efficiency have been recognized as crucial approaches to efficient water use (Nemali, van Iersel 2008). The water use efficiency of the plants can be estimated from the biomass and the amount of NS that was retained by the substrate (i.e., NS applied – leached). The 'Θ = 0.3' treatment resulted in the highest WUE_r, and there was no difference in WUE_r between the 'Timer' and 'Θ = 0.4' treatments (Table 1).

However, when calculating water use efficiency, it is also important to account for the change in the amount of water present in the substrate over the course of the growing cycle. The Θ did not change much in the 'Timer' and 'Θ = 0.4' treatments, but decreased from 0.48 to 0.30 m^3/m^3 (approximately 900 ml/container) in the 'Θ = 0.3' treatment. Taking into account this additional amount of water used by the plants in the 'Θ=0.3' treatment reduces the WUE_r to approximately 3.1 g/l, similar to that in the other treatments.

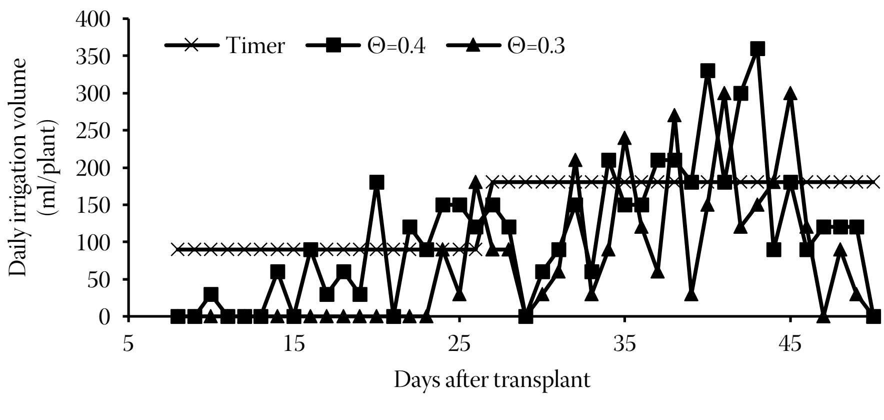

Fig. 2. Daily irrigation volume for lettuce plants irrigated with a timer or with an automatic irrigation system based on Θ threshold (0.30 for 'Θ=0.3' and 0.40 m^3/m^3 for 'Θ=0.4') measured by substrate moisture sensors

doi: 10.17221/312/2014-HORTSCI

Table 2. Leaf area and number, total fresh and dry weight, and total dry matter of lettuce plants grown in soilless conditions and with irrigation management performed with a timer or with an automatic irrigation system based on Θ threshold (0.30 m^3/m^3 for 'Θ = 0.3' and 0.40 m^3/m^3 for 'Θ = 0.4') measured by substrate moisture sensors

Treatment	Leaf area (cm^2/plant)	Leaf number per plant	Total fresh weight (g/plant)	Total dry weight (g/plant)	Dry matter (%)
Timer	3,914^a	36	273.3^a	12.5	4.58^b
Θ = 0.4	3,889^a	33	267.0^a	13.0	4.87^b
Θ = 0.3	3,446^b	33	217.1^b	12.3	5.67^a
Significance[1]	*	ns	*	ns	**

[1]mean separation within columns by $LSD_{0.05}$; ns, *, ** – non-significant or significant at $P \leq 0.05$ and $P \leq 0.01$, respectively; within columns, values followed by the same letters are not significantly different

Electrical conductivity was slightly higher in the 'Θ = 0.3' treatment (Table 1), likely because of the absence of leaching and accumulation of fertilizer salts. Similar results were observed by Burnett and van Iersel (2008). High substrate EC may negatively affect plant growth by imposing osmotic stress. This is a potential problem that should be taken into account when using sensor-controlled irrigation, especially with salt-sensitive species or low quality (high EC) irrigation water.

Plant growth, photosynthetic activity and tissue analysis

At the end of the growing cycle, plants had a similar number of leaves in all treatments, but the plants irrigated at the lowest Θ showed, on average, a 11.7% decrease in leaf area (Table 2). Plants in the 'Timer' and 'Θ = 0.4' treatments had higher fresh weights (24%) than plants irrigated at the lowest Θ threshold (Table 2). No differences in dry weight were observed among treatments. Thus, the irrigation treatments had little or no effect on biomass production, and differences in fresh weight resulted from differences in plant water content. Percent dry matter was 20% higher in the 'Θ = 0.3' treatment than in the treatments with higher fresh weights. In minimally-processed greens, a high dry matter percentage is desirable because low dry matter content can decrease shelf life (Manzocco et al. 2011). Our results suggest that precision irrigation can be used to increase dry matter content, thereby improving the quality of lettuce in soilless cultivation. The 'Θ = 0.3' plants irrigated at the lowest Θ, showed, on average, an 11.7% decrease in leaf area (Table 2). Reduced water availability leads to decreased leaf size because even mild drought can reduce the turgor needed for cell expansion during leaf development (Boyer 1970). Water availability in soilless substrates is reduced rapidly when Θ approaches a substrate-specific threshold (Wallach 2008) and the 'Θ = 0.3' treatment apparently imposed enough of drought stress to reduce leaf elongation. The reduced leaf area in this experiment was consistent with the lower tissue water content observed in the 'Θ = 0.3' treatment, in which Θ was maintained below the generally recognized limit for EAW in soilless substrates (de Boodt, Verdonck 1972; Argo 1998). However, no visual symptoms of water stress were observed in any of the plants, indicating that the drought stress in the 'Θ=0.3' treatment was not severe. This was consistent with the lack of an effect on shoot biomass.

Leaf chlorophyll content, net CO_2 assimilation rate, stomatal conductance and leaf transpiration were similar in all treatments (Table 3). Since gas exchange parameters were similar, WUE_i was also similar for all treatments. However, WUE_a was higher in the sensor-controlled treatments (Table 1). Leaf gas exchange measurements are limited to a particular leaf and specific time, and may not accurately represent long-term or whole-plant processes. When calculated using leaf gas exchange measurements, WUE is not always consistent with the final WUE based on biomass and yield (Gulías et al. 2012; Tomás et al. 2012; Wang et al. 2013). In this study, it was demonstrated that, although WUE_i was unaffected, the overall water use efficiency (WUE_a) of an irrigation system can be improved by adopting sensor-control.

Leaf tissue chemical composition was not affected by the treatments, with the exception of nitrate concentration, which was lowest in the "Θ = 0.3" treatment (Table 4). This may be because less NS, and thus less nitrate, was applied in the 'Θ = 0.3'

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Table 3. Chlorophyll content, net CO_2 assimilation rate (A_n), stomatal conductance to water vapour (g_{sw}), leaf transpiration (T) and instantaneous water use efficiency (A_n/T, WUE_i) of lettuce plants grown in soilless conditions and with irrigation management performed with a timer or with an automatic irrigation system based on Θ threshold (0.30 m^3/m^3 for 'Θ = 0.3' and 0.40 m^3/m^3 for 'Θ = 0.4') measured by substrate moisture sensors

Treatment	Chlorophyll content (SPAD units)	A_n (μmol/m^{2}s)	g_{sw} (mol/m^{2}s)	T (mmol/m^{2}s)	WUEi (μmol/mmol)
Timer	33.9	18.8	0.94	4.74	3.98
Θ = 0.4	33.6	18.8	0.81	4.80	3.94
Θ = 0.3	34.5	19.4	0.78	4.46	4.40
Significance[1]	ns	ns	ns	ns	ns

[1]mean separation within columns by $LSD_{0.05}$; ns – non-significant

treatment (Table 1). Moreover, a strong negative correlation between nitrate and dry matter content has been demonstrated in butterhead lettuce cultivars (Reinink et al. 1987), similar to our findings. This relationship between nitrate and dry matter content is explained by the fact that a high dry matter content is normally associated with high organic solutes in the cell vacuole (Reinink, Blom-Zandstra 1989), thus reducing the plant accumulation of nitrates to compensate for a lower concentration of organic solutes (Reinink 1993). However, none of the plants showed any visual symptom of nitrogen deficiency and leaf chlorophyll readings were similar in all treatments, suggesting that nutritional needs were met in all treatments. High nitrate concentrations in leafy greens can be a health hazard, and in some cases (i.e., European countries), regulations limit the acceptable nitrate concentration of vegetables. Precision irrigation could be used to improve lettuce quality by reducing leaf nitrate concentrations.

Table 4. NO_3, K, Mg and Ca content (g/kg dry weight) in leaf tissues of lettuce plants grown in soilless conditions and with irrigation management performed with a timer or with an automatic irrigation system based on Θ threshold (0.30 for 'Θ = 0.3' and 0.40 m^3/m^3 for 'Θ = 0.4') measured by substrate moisture sensors

Treatment	NO_3	K	Mg	Ca
Timer	55.0^a	89.2	5.6	13.4
Θ = 0.4	49.5^a	90.9	5.1	11.0
Θ = 0.3	33.4^b	74.8	5.7	13.7
Significance[1]	***	ns	ns	ns

[1]mean separation within columns by $LSD_{0.05}$; ns, *** – non-significant and significant at $P \leq 0.001$, respectively; within columns, values followed by the same letters are not significantly different

Potential economic impact

Sensor-controlled irrigation can have a positive economic impact on greenhouses through a variety of ways: reducing water cost, less energy required to pump water, labour savings resulting from automation, improved crop quality and/or shorter production cycles. Some of these potential benefits will differ based on locations, since the cost of water, energy, and labour varies. In one case study in the South-eastern United States, it was shown that precision irrigation using wireless sensor networks increased annualized profits of the production of *Gardenia jasminoides* by 156% (Lichtenberg et al. 2013). This increase in profits resulted largely from better growth and a shorter production cycle, and to a lesser extent from a reduction in plants lost due to damage by root pathogens. No similar economic analysis has yet been conducted for lettuce production.

A survey of US greenhouse and nursery growers showed widespread interest in adoption of wireless sensor networks for sensor-controlled irrigation. Lichtenberg et al. (2015) suggested that the initial adoption rate of wireless sensor networks may be high, based on the expected cost of such systems and the growers' willingness to pay for them. Whether this holds true in other parts of the world is not yet clear.

In conclusion, sensor-controlled irrigation with a set-point above the EAW limit ('Θ = 0.4' treatment) had similar plant fresh weight and quality as timer-controlled irrigation, but used less irrigation volume. Maintaining a substrate moisture lev-

doi: 10.17221/312/2014-HORTSCI

el slightly below the conventionally defined EAW (‘Θ = 0.3’ treatment) range reduced the water content and nitrate concentration of lettuce grown in soilless substrate but did not reduce overall biomass production. Sensor-controlled irrigation resulted in higher overall water and nutrient use efficiency than timer-controlled irrigation. Precision irrigation based on Θ measurements eliminated leaching while improving the quality of soilless-grown lettuce.

Acknowledgement

We thank Gerolmina Florio and Nicola Gentile for their technical assistance and Geoffrey Weaver for editing this manuscript.

References

Anonymous (2000): Establishing a framework for community action in the field of water policy (Water Framework Directive), 2000/60/EC, L327.

Argo W. (1998): Root medium physical properties. HortTechnology, 8: 481–485.

Altland J.E., Owen Jr J.S., Fonteno W.C. (2010): Developing moisture characteristic curves and their descriptive functions at low tensions for soilless substrates. Journal of American Society for Horticultural Science, 135: 563–567.

Blackstock K.L., Ingram J., Burton R., Brown K.M., Slee B. (2010): Understanding and influencing behaviour change by farmers to improve water quality. Science of The Total Environment, 408: 5631–5638.

Boyer J.S. (1970): Leaf enlargement and metabolic rates in corn, soybean, and sunflower at various leaf water potentials. Plant Physiology, 46: 233–235.

Burnett S.E., van Iersel M.W. (2008): Morphology and irrigation efficiency of *Gaura lindheimeri* grown with capacitance sensor-controlled irrigation. HortScience, 43: 1555–1560.

De Boodt M., Verdonck O. (1972): The physical properties of the substrates in horticulture. Acta Horticulturae (ISHS), 26: 37–44.

Dukes M.D., Zotarelli L., Morgan K.T. (2010): Use of irrigation technologies for vegetable crops in Florida. HortTechnology, 20: 133–142.

Elia A., Santamaria P., Serio F. (1996): Ammonium and nitrate influence on artichoke growth rate and uptake of inorganic ions. Journal of Plant Nutrition, 19: 1029–1044.

Fallovo C., Rouphael Y., Rea E., Battistelli A., Colla G. (2009): Nutrient solution concentration and growing season affect yield and quality of *Lactuca sativa* L. var. *acephala* in floating raft culture. Journal of the Science of Food and Agriculture, 89: 1682–1689.

Gulías J., Seddaiu G., Cifre J., Salis M., Ledda L. (2012): Leaf and plant water use efficiency in cocksfoot and tall fescue accessions under differing soil water availability. Crop Science, 52: 2321–2331.

Johnson C.M., Stout P.R., Broyer T.C., Carlton A.B. (1957): Comparative chlorine requirements of different plant species. Plant and Soil, 3: 337–353.

Jones H.G.(2007): Monitoring plant and soil water status: Established and novel methods revisited and their relevance to studies of drought tolerance. Journal of Experimental Botany, 55: 2427–2436.

Jury W.A., Vaux H. (2005): The role of science in solving the world’s emerging water problems. In: Proceedings of the National Academy of Sciences of the United States of America, 102: 15715–15720.

Kläring H.P. (2001): Strategies to control water and nutrient supplies to greenhouse crops. A review. Agronomie, 21: 311–321.

Lichtenberg E., Majsztrik J., Saavoss M. (2013): Profitability of sensor-based irrigation in greenhouse and nursery crops. HortTechnology, 23: 770–774.

Lichtenberg E., Majsztrik J., Saavoss M. (2015): Grower demand for sensor-controlled irrigation. Water Resources Research, 51: 341–358.

Manzocco L., Foschia M., Tomasi N., Maifreni M., Dalla Costa L., Marino M., Cortella G., Cesco S. (2011): Influence of hydroponic and soil cultivation on quality and shelf life of ready-to-eat lamb’s lettuce (*Valerianella locusta* L. Laterr). Journal of the Science of Food and Agriculture, 91: 1373–1380.

Naasz R., Michel J.C., Charpentier S. (2005): Measuring hysteretic hydraulic properties of peat and pine bark using a transient method. Soil Science Society of America Journal, 69: 13–22.

Nemali K., van Iersel M. (2006): An automated system for controlling drought stress and irrigation in potted plants. Scientia Horticulturae, 110: 292–297.

Nemali K., van Iersel M. (2008): Physiological responses to different substrate water contents: screening for high water-use efficiency in bedding plants. Journal of the American Society for Horticultural Science, 133: 333–340.

Nemali K.S., Montesano F., Dove S.K., van Iersel M.W. (2007): Calibration and performance of moisture sensors in soilless substrates: ECH_2O and Theta probes. Scientia Horticulturae, 111: 227–334.

Reinink K. (1993): Relationship between effects of seasonal change on nitrate and dry matter content in lettuce. Scientia Horticulturae, 53: 35–44 .

Reinink K., Blom-Zandstra M. (1989): The relation between cell size, ploidy level and nitrate concentration in lettuce. Physiologia Plantarum, 76: 575–580.

doi: 10.17221/312/2014-HORTSCI

Reinink K., Groenwold R., Bootsma A. (1987): Genotypical differences in nitrate content in *Lactuca sativa* L. and related species and correlation with dry matter content. Euphytica, 36: 11–18.

Scuderi D., Restuccia C., Chisari M., Barbagallo R.N., Caggia C., Giuffrida F. (2011): Salinity of nutrient solution influences the shelf-life of fresh-cut lettuce grown in floating system. Postharvest Biology and Technology, 59: 132–137.

Selma M.V., Luna M.C., Màrtinez-Sànchez A., Tudela J.A., Beltràn D., Baixauli C., Gil M.I. (2012): Sensory quality, bioactive constituents and microbiological quality of green and red fresh-cut lettuces (*Lactuca sativa* L.) are influenced by soil and soilless agricultural production systems. Postharvest Biology and Technology, 63: 16–24.

Shock C.C., Wang F.-X. (2011): Soil water tension, a powerful measurement for productivity and stewardship. HortScience, 46: 178– 85.

Tomás M., Medrano H., Pou A., Escalona J.M., Martorell S., Ribas-Carbó M., Flexas J. (2012): Water-use efficiency in grapevine cultivars grown under controlled conditions: effects of water stress at the leaf and whole-plant level. Australian Journal of Grape and Wine Research, 18: 164–172.

Valenzano V., Parente A., Serio F., Santamaria P. (2008): Effect of growing systems and cultivar on yield and water use efficiency of greenhouse-grown tomato. The Journal of Horticultural Science and Biotechnology, 83: 71–75.

van Iersel M. W., Dove S., Kang J.G., Burnett S.E. (2010): Growth and water use of petunia as affected by substrate water content and daily light integral. HortScience, 45: 277–282.

van Iersel M.W., Chappell M., Lea-Cox J.D. (2013): Sensors for improved irrigation management in greenhouse and nursery production. HortTechnology, 23: 735–746.

Wallach R. (2008): Physical characteristics of soilless media. In: Raviv M., Lieth J.H. (eds): Soilless Culture: Theory and Practice. Amsterdam, Elsevier: 41–116.

Wang Y., Zhang X., Liu X., Zhang X., Shao L., Sun H., Chen S. (2013): The effects of nitrogen supply and water regime on instantaneous WUE, time-integrated WUE and carbon isotope discrimination in winter wheat. Field Crop Research, 144: 236–244.

Yeager T., Fare D., Gilliam C., Niemiera A., Bilderback T., Tilt K. (1997): Best management practices guide for producing container-grown plants. Southern Nurserymen's Assn., Marietta, GA.

Received for publication November 19, 2014
Accepted after corrections September 7, 2015

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