Use of a low-cost soil moisture sensor to reduce irrigation water usage in mild winter climate greenhouses

I.H. Tüzel[a], J. Balendonck[2,b], Y. Tüzel[3], G.B. Öztekin[3] and U. Tunali[1]

[1]Ege University, Faculty of Agriculture, Department of Agriculture Structures and Irrigation, Bornova-İzmir, Turkey; [2]Wageningen University and Research, Greenhouse Horticulture, Wageningen, The Netherlands; [3]Ege University, Faculty of Agriculture, Department of Horticulture, Bornova-İzmir, Turkey.

Abstract

Fresh water sources are becoming scarce. Crop irrigation uses more than 70% of the world's water, and thus, improving irrigation efficiency and saving water is key to sustaining the food demands of a fast-growing world population. Manually controlling irrigation often leads to over dosing and excess nutrients drain from the soil. Soil sensor activated irrigation is an important step in improving water use efficiency. By using sensors, irrigation water can be controlled more precisely to prevent excessive drainage and fertilizer leaching or even under dosing leading to yield reduction. Over the past decades, soil moisture sensor technology has been improved a lot, and meanwhile a large variety of TDR and FDR sensors with good performance are available. Water content may vary within an irrigated field. Since sensors only measure locally and existing sensors are relatively expensive, use of more sensors per field can become costly. The AquaTag is a prototype low-cost, wireless, near-field, passive, capacitance resonance type soil moisture sensor which can be read-out using a hand-held reading device. To help small-scale and low-tech farmers in saving water, we evaluated a simple irrigation support system making use of this sensor. The support system advises upon soil water activation levels and dosing taking crop stage and soil hydraulics into account, as well as the average water content of an irrigated plot obtained with the sensors. Its potential for useability was demonstrated in nine Turkish commercial farms with soil-grown vegetables. Farmers using the sensors were able to raise their irrigation water productivity on average with 22.9% as compared to farmers not using the sensors. The prototype performed well, but it should be further developed toward a sensor that can measure at rooting depth up to 30-60 cm.

Keywords: water use efficiency, contactless, RF tag, soil water content, horticulture

INTRODUCTION

Soil sensor activated irrigation scheduling

Irrigation water availability is becoming a major limiting factor, especially in regions suffering from incidental seasonal or structural drought. Rosegrant et al. (2002) expected that irrigated agriculture by 2025 will increase by at least 50% compared to 1995, and proposed investing in the irrigation infra-structure, conserving water, improving water use efficiency and improving crop productivity per unit of water and land. Irrigation Water productivity (WP_I) affects farmers' economic returns most and so it is used as an index to compare cropping system efficiencies. It is defined as the ratio between the marketable yield (Y in kg) produced by a crop along the growing season and the irrigation water used (IWU) in the same period (Fernández et al., 2020). Farmers may enhance WP_I by optimizing their irrigation equipment and cropping system. For instance, several methods could be employed, closed pipes instead of open channels being used to avoid leakage and evaporation, drip instead of

[a]Died October 19, 2019

[b]E-mail: jos.balendonck@wur.nl

Acta Hortic. 1373. ISHS 2023. DOI 10.17660/ActaHortic.2023.1373.17
XXXI IHC – Proc. IS. on Water: a Worldwide Challenge for Horticulture!
Eds.: B. Morandi and M. Kuper

furrow or sprinkler irrigation is used to enhance water application efficiency, or crops being grown in greenhouses using hydroponics rather than soil. To further maximize WP_I, farmers must match water supply with actual crop water demand and for that be able to make sound decisions about irrigation timing and dose. A common approach for this is to estimate daily crop water demand based on climatic data by using an ET-model like the FAO56 Penman-Monteith equation (Allen et al., 1998). This model requires input for a coefficient (K_c) which is dependent on crop growth stage. This approach is a feed-forward control system, but it has some issues. With no feedback about actual soil water status, it may lead to under- or over-irrigation. An alternative way to manage irrigation is by using feedback to prevent under- or over-irrigation, is to apply Soil Sensor *Activated* Irrigation Scheduling (SSAIS). Dukes et al. (2003), Zotarelli et al. (2008) and Balendonck et al. (2010) showed that by using soil sensors, water savings can be obtained, ranging from 33 to 80%. Here irrigation is based on feedback about plant available water (PAW) in the root zone, which is the difference between the water content at field capacity (FC) and permanent wilting point (PWP). As not all of the PAW is readily available for crops, a threshold value for water content to start an irrigation event is used, derived from a desired management allowable depletion (MAD) factor given as a certain percentage (0-100%). SSAIS is described exhaustively in literature and De Pascale et al. (2018) describe the state of the art of using soil sensors for irrigation scheduling of vegetables. Time domain reflectometry (TDR) and frequency domain (FDR) sensors are mostly applied with this technique (Zinkernagel et al., 2020).

Soil sensor supported irrigation scheduling

SSAIS is becoming widespread under intensive large-scale and high-tech farming systems. However, in small-scale and low-tech farms, it is not commonly used especially in poorer countries, where farms smaller than 2 ha account for 70% of total farms (Adamapoulos and Restuccia, 2011). Investment, operating and maintenance costs must be recovered by extra income from water, fertilizer, or energy reduction or from higher yields and better crop qualities. Soil sensor application also demands new skills and with little external support, poorly trained, farmers, might not be able to adopt it. All this impedes their possibilities to enhance irrigation water productivity (Balendonck et al., 2010).

The Mediterranean and Aegean region in Turkey is a good example for this as it is estimated that more than 98% of the greenhouse production area is soil-based vegetable production (e.g., cucumber, lettuce, tomato, pepper, eggplant and French beans) in low-tech greenhouses (including low plastic tunnels, shading nets), at a size of less than 1.0 ha, operated by 100,000 farmers (Tüzel and Öztekin, 2016). Greenhouses are mostly polyethylene covered. Drip-irrigation is used, but water and fertilizer management are done with simple, non-automated tools. Some have simple fertigation equipment, like a mixing tank and storage. Irrigation water is pumped up from groundwater wells and irrigations are started manually, based upon visual observations. A few use tensiometers with manually read-out pressure indicators to monitor soil water status. Many of these farmers hesitate to change over to substrate cultivation, either due to high investments or a lack of knowledge.

In the Aegean region, around İzmir, the Tahtali Dam supplies drinking water to the city. Authorities have recently issued regulations discouraging fertilizer leaching into the dam catchment area to prevent pollution. Farmers now need to irrigate with more precision to reduce fertilizer leaching. Balendonck et al. (2010) evaluated a SSAIS and demonstrated the potential to save fresh water and reduce fertilizer leaching while maintaining acceptable product yield. For drip-irrigated cucumber a reduction of 19% in water use and nearly zero fertilizer leaching was achieved by preventing over-irrigation events. Plant stress and yield losses due to under-irrigations were prevented by timely irrigation events triggered by soil moisture sensors (Tüzel et al., 2009). However, introduction of SSAIS on a wider scale would be a considerable challenge and a too costly approach for the farmers, as they cannot afford sophisticated equipment and have only little support from advisory services or suppliers. Their current irrigation practice is to just inspect their soil and if needed, to manually opening valves to irrigate. The addition of sensors could help, but farmers must be able to install and use those based on simple guidelines. In addition, equipment and work methods must be low-

cost and properly geared to the needs and practices of the existing farmers. Therefore, we suggest using low-cost soil sensors combined with "Soil Sensor Supported Irrigation Scheduling" (SSSIS). This is different from SSAIS because the irrigation is not truly automated, as farmers are only advised upon the irrigation moment (the refill-point, a threshold for water content) based on the average value of the water content in the field, manually obtained from a number of installed soil sensors. The opening and closing of irrigation valves are kept under full control of the farmer, and the irrigation dose is obtained from a simple calculation sheet with inputs for the crop, crop stage and soil type. To what extent optimum irrigation will be achieved depends so fully on the willingness of the farmer to follow the irrigation advice.

This approach aims to support enhancing irrigation water productivity by use of soil moisture sensors at low investment cost. However, using soil sensors to monitor water availability under farmer's operational conditions is often not so straight-forward, as much evidence has shown in the last two decades (Pardossi et al., 2009; Zinkernagel et al., 2020). Among others, Vera et al. (2021) give an overview about factors affecting sensor performance. Common soil moisture sensors measure soil dielectric permittivity and relate this to soil water content (SWC in m^3 m^{-3}). Variations in soil properties like texture, bulk density and presence of stones including salinity, all have a substantial effect on this relation and therefore a soil-specific calibration is advised. As it is difficult and time consuming to obtain individual calibration curves for each sensor position and depth, standard soil type calibrations are mostly used. Heterogeneity in soil hydraulic properties also affects the water distribution within a plot, and as sensors give point related data, use of a single or a limited number of sensors may lead to larger errors in the averaged SWC for a plot. How many locations per plot a sample is required to obtain an accurate average water content depends on the spatial and temporal SWC variability. Brocca et al. (2007) found for small-sized Italian fields that 20-35 independent soil moisture samples were required to get a mean SWC at an error of ±2%. Zotarelli et al. (2013) suggests a more practical approach by identifying homogeneous zones per plot, and then placing 1-3 sensors in each zone. Further it is advisable to insert a sensor only once and keep it in place, to get reproducible readings over time. This indicates better that an irrigation event is always triggered at the same level, even though SWC itself may not be well-calibrated. In this study we hypothesize that when soil water spatial variability is large with respect to sensor accuracy, an average SWC of an irrigated field obtained with multiple lesser accurate sensors, may even be more accurate than obtained with a single more accurate sensor. Therefore, we wanted to use multiple low-cost sensors in a field.

Adla et al. (2020) concluded that low-cost capacitive sensors are suitable to be used for irrigation scheduling after a soil specific calibration. However, use of sensors requires additional equipment, and including interfacing, the cost per sensing point currently is higher than $ 100. This is still too expensive for small-scale farmers. Balendonck et al. (2013) described a wireless near-field passive capacitance soil water content sensor tag. It uses the soil as a capacitor to obtain soil water content by measuring the resonant frequency of the electrical circuit formed by the soil electrodes and an inductor (Hilhorst and Doodeman, 2010). A manual action is needed to interrogate sensor tags with a read-out device up to a distance of 5 cm. Balendonck et al. (2021) evaluated the performance of sensor and reader prototypes (AquaTag, SensorTagSolutions BV, Rotterdam, NL). With ±10% it is not as accurate as common TDR or FDR sensors, but at very large quantities it can potentially be produced at very low costs (about $ 10). The goal of this work was to apply a SSSIS making use of the AquaTag and to evaluate its performance and water saving capabilities. Our target was to optimize marketable crop yield (in kg m^{-2}) in relation to water use (in m^3) for small-scale, low-tech horticulture farms in arid regions with vegetable production.

MATERIALS AND METHODS

This study was carried out at vegetable growing farms in Orhanlı village-Seferihisar/İzmir (38°09'N, 26°57'E, elevation 115 m). The area has a Mediterranean climate, with mild and rainy winters. Vegetable crops, conventional and organic production, are grown year-around in several cycles with a break during the hot and dry summers. Trials were conducted during three growing cycles (1, 2, 3) in 2013-2014 at selected plots of nine local

farms (Table 1).

Table 1. Overview of the experiments with crop types, farms, plots and treatments.

Crop	Plot[b]	Treatment	Start date	Duration (d)	Crop cycle
Cucumber 1[a]	1a	Sensor	18.5.2013	92	1
	2a	Farmer	5.5.2013	70	1
Lettuce[a]	1a	Sensor	27.11.2013	120	2
	2a	Farmer			2
Cucumber[a]	1a	Sensor	21.05.2014	73	3
	2a	Farmer	17.04.2014	82	3
Tomato[a]	3a	Sensor	29.06.2013	127	1
	3b	Farmer			1
Lettuce[a]	3a	Sensor	18.11.2013	151	2
	3b	Farmer			2
Pepper[a]	3a	Sensor	15.05.2014	197	3
	3b	Farmer			3
Tomato	4a	Sensor	14.05.2014	115	3
	4b	Farmer			3
Cucumber	4a	Sensor	21.4.2013	181	1
	5a	Farmer			1
Lettuce	5a	Sensor	21.10.2013	103	2
	5b	Farmer			2
Cucumber 2	5a	Sensor	24.05.2014	170	3
	5b	Farmer			3
French bean	6a	Sensor	5.4.2013	187	1
	7a	Farmer			1
Eggplant	6a	Sensor	26.04.2014	216	3
	6b	Farmer			3
Pepper	8a	Sensor	27.4.2013	190	1
(open field)[a]	9a	Farmer			1

[a]Organic production.
[b]Multiple plots at a farm are indicated with a, b.

Farms had plastic covered greenhouses, except for farm 8 and 9, having open field production. Each plot had one valve section and varied in size between 40 and 60 m^2. Drip-irrigation was used; the laterals are laid on each plant row, having built-in emitters spaced at 25 cm, with a discharge rate of 2-4 L h^{-1}. Systems operate with around one bar at the beginning of the laterals. Control consists of a pump with disk filters, valves, and a simple fertilizer and mixing tank. Farm soils contained mixtures of sand, loam and clay, and for each farm, FC, PWP and bulk density (BD) were obtained by laboratory analyses (Table 2).

Two treatments were used (Table 1), one in which farmers used sensors for irrigation ("sensor"), and one where farmers did not use the sensor ("farmer"). For WP_I comparison, treatments were paired to have the same crop type and growing cycle. Crop production for each plot was obtained directly after harvest by weighing the marketable production and total water use was monitored with flow meters, from which WP_I was then calculated. For in total 13 paired plots, a water saving index (WSI), expressed as a percentage, was obtained from the ratio of WP_I of the treatments by using: $WSI = (WP_I(sensor)/WP_I(farmer)-1).100\%$.

Table 2. Soil physical properties per farm in the soil layer 0-30 cm.

Plot	Texture[b]	Field capacity (%)	Permanent wilting point (%)	Bulk density (g cm^{-3})
1a	SCL	44.9	21.8	1.30
2a	SCL	44.5	22.2	1.48
3ab	SL	36.9	17.9	1.44
4ab	SCL	42.4	16.7	1.36
5ab	SL	33.4	12.8	1.44
6ab	SL	37.5	14.9	1.50
7a	SL	37.7	15.5	1.52
8a[a]	SL	23.5	10.5	1.46
9a[a]	SL	23.8	10.7	1.46

[a]Open field production field production.
[b]Sandy (S), Clay (C), Loam (L).

In sensor treatments, five sensors at a spacing of 4-5 m were placed on a plant row in the middle of the first soil layer at 15 cm depth, surrounded with a PVC-jacket (Ø 15 cm), covered with a lid (Figure 1). Measurements were carried out by farmers once per day with the AquaTag reader. SWC (in %) was obtained with the loamy-clay soil type calibration function obtained by Balendonck et al. (2021).

Figure 1. AquaTag with a PVC jacket in cucumber, reader and drip-irrigated French beans.

Since radio signals do not propagate well through wet soils, and prototypes were only available as a short version, the AquaTag could not be used at deeper root zone (30-60 cm). Therefore, a soil moisture sensor connected to a datalogger (ML2 and GP1, Delta-T Devices, Burwell, Cambridge, UK) was placed at a depth of 45 cm. A meteorology station was placed in the experimental area at a representative point for the climate, and air temperature, relative humidity, wind speed, solar radiation and precipitation were collected to estimate daily crop water demand by using the FAO56 Penman-Monteith (PM) equation (Allen et al., 1998). Farmers' decisions to start an irrigation were based on the obtained average SWC using the AquaTag at 15 cm depth. Irrigation was started when SWC reached a static threshold value based on MAD (20%) depletion of PAW, calculated according to the soil properties in layer 0-30 cm from Table 2. Farmers were visited every five days for sensor and water meter data recording as well as for updating the farmer's irrigation advice. Irrigation dose advice was varied according to FAO56 guidelines (Allen et al., 1998) based on the soil water depletion in the deeper root zone (30-60 cm), taking into account soil type (FC, PWP, BD), MAD, wetted area of sprinklers and the effective rooting depth depending on crop stage (Table 3).

Table 3. Irrigation start (refill point) and stop (dose) advice for sensor-controlled plots.

Plots	1-2a	3ab	4ab	5ab	6ab	7a	8-9a
SWC refill point (%)	36	33	35	28	27	27	22
Average dose (mm)[a]	11	10	12	11	11	11	8

[a]Doses varied during cropping, therefore average doses per plot over the cropping period are shown.

RESULTS

The daily readings (n=5) obtained with the AquaTag showed a standard deviation of not more than 2.6% over all readings and plots. Obtained marketable yield, used water, calculated WP_I for each plot, as well as the treatment comparisons resulting in a WSI per treatment pair are shown in Table 4. Applied irrigation water and marketable yield varied per crop, farmer, cycle length and treatment. Farmers using sensors applied 9-40% less water, and achieved higher irrigation water productivities, from 1.05 up to a factor of 2.03, than farmers having no sensors for a similar crop and cropping period. For five sensor treatments, marketable yield was equal or up to 18% higher than for the farmer treatments while in the other cases, farmers achieved a higher yield (1-14%). Farmers stated that there were no differences in fruit quality. Farmers with conventional production rated their marketable yield as acceptable. Though, organic farmers achieved lower yields, which was related to problems with pest and diseases. Farmers using sensors were significantly better ($P(T \leq 0.01)$) in utilizing water for crop production, as their water savings compared to farmer treatments varied from 2.5 to 50.6% and was on average 22.9%.

Table 4. Obtained results for all plots, including the calculated water saving index.

Crop	Plot	Treatment	Irrigated water (mm)	Marketable yield (kg m^{-2})	WP_I (kg m^{-3})	Water saving index (%)
Cucumber 1[a]	1a	Sensor	733	6.25	8.53	2.5
	2a	Farmer	802	6.67	8.32	
Lettuce[a]	1a	Sensor	128	5.00	39.1	16.3
	2a	Farmer	153	5.00	32.7	
Cucumber[a]	1a	Sensor	336	6.65	19.8	5.0
	2a	Farmer	404	7.60	18.8	
Tomato[a]	3a	Sensor	679	2.00	2.95	18.7
	3b	Farmer	940	2,25	2.39	
Lettuce[a]	3a	Sensor	329	7.50	22.8	25.9
	3b	Farmer	444	7.50	16.9	
Pepper[a]	3a	Sensor	656	5.23	8.0	46.3
	3b	Farmer	1084	4.64	4.3	
Tomato	4a	Sensor	971	12.10	12.5	28.4
	4b	Famer	1412	12.60	8.9	
Cucumber	4a	Sensor	613	14.98	24.44	50.6
	5a	Farmer	895	10.80	12.07	
Lettuce	5a	Sensor	132	5.00	37.9	19.5
	5b	Farmer	164	5.00	30.5	
Cucumber 2	5a	Sensor	940	8.50	9.0	14.2
	5b	Farmer	1199	9.30	7.8	
French bean	6a	Sensor	406	3.95	9.73	23.6
	7a	Farmer	538	4.00	7.43	
Eggplant	6a	Sensor	1318	7.76	5.9	14.2
	6b	Farmer	1549	7.83	5.1	
Pepper (open field)[a]	8a	Sensor	812	1.82	2.2	12.3
	9a	Farmer	993	1.95	2.0	

[a]Organic production.

Figure 2 gives the applied irrigation water for sensor and farmer treatments. Although most farmers tried to follow the irrigation advice, they generally applied more water than advised by the SSSIS. As compared to the PM estimated crop water needs, farmers not using sensors applied 14.5-91.2% (on average 56.9%) times more water, whereas in sensor treatments farmers only applied -5.2-38.3% (on average 18.7%) more water than advised.

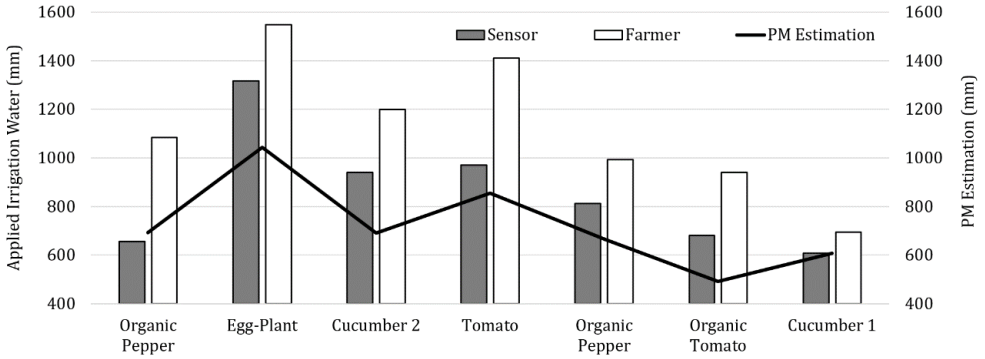

Figure 2. Applied water in all treatments as compared to PM estimated crop water needs.

DISCUSSION

For the AquaTag one calibration was used for all soil types. No temperature or EC corrections were done as suggested by Pardossi et al. (2009). Zotarelli et al. (2013) suggested 1-3 sensors at well-chosen locations. Not knowing the dryer and wetter spots in the fields a-priori, we used five sensors at fixed locations. The AquaTag readings showed low standard deviations (<2.6%) falling within the ±10% accuracy range Balendonck et al. (2021) found. Maybe the plots were very homogeneous. However, it would require more research to conclude that lesser sensors could have been used. Most water for mature vegetables is extracted from deeper layers (Allen et al., 1998) and Balendonck et al. (2010) also showed that monitoring at a deeper layer is required. As we could not measure with the AquaTag below 15 cm, another sensor was used in the deeper layers. This was an acceptable workaround, but it required intervention by the researchers. For practical use, the AquaTag must be enlarged to at least 30-60 cm to be able to also measure in the deeper root zone.

In spite of the AquaTag shortcomings, the SSSIS performed well. Farmers who used sensors obtained larger water savings between 2.5 and 50.6% as compared to farmers who did not use the sensors. The average of 22.9% is comparable with the 19% found by Tüzel et al. (2009). Only two farmers achieved very large water savings (46.3, 50.6%) which is comparable with the 40% Vera et al. (2021) reported. However, it should be noted that the obtained water savings were largely due to the individual farmer's attitude toward irrigation water use. Most farmers generally applied more water than advised by the PM-estimation (Allen et al., 1998). It is likely that they could have saved more water by following the advice, more closely, but there was a lack of motivate by the farmers to pay attention to the advice. During this trial the farmers experienced no real water scarcity and were not motivated to use the SSSIS except to conform to the legislation for emission.

CONCLUSIONS

A simple irrigation advisory tool making use of a prototype low-cost soil water content sensor was presented. Its performance to optimize irrigation water productivity was studied at nine vegetable growing farms in Turkey. Farmers using sensors, as compared to farmers not using sensors, enhanced irrigation water productivity by 2.5-50.6%. Although most farmers followed the irrigation advice, they generally applied more water. Farmers not using sensors applied on average 56.9% more water, whereas farmers using sensors only applied 18.7% more. All farmers with conventional production reported no notable yield losses or differences in quality. The AquaTag prototype showed potential to be used in low-tech

vegetable production for optimizing irrigation performance, but sensors with a longer shaft are required to use it at crop rooting depths up to 30-60 cm.

ACKNOWLEDGEMENTS

This work was supported by the Dutch Ministry of Infrastructure and Environment under the program "Partners for Water", with reference: PVWS12003. We thank the farmers of the Orhanli Village (Turkey) who provided access to their greenhouses for field testing.

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