SOIL MOISTURE LEVELS AND WATER CONSUMPTION IN PROCESSING TOMATO. COMPARISON BETWEEN HIGH FRECUENCY DRIP IRRIGATION SCHEDULED BY ETc AND CONTROLLED BY CAPACITANCE AND GRANULAR MATRIX SENSORS

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RESUMEN. Con el fin de evaluar el uso de sensores de humedad de suelo para el control de riego en un cultivo de tomate para industria (*Lycopersicum esculentum,* Mill), se utilizaron tres tipos de programación de riego: riego de acuerdo a la ETc (ET_1), riego controlado por sensores de capacitancia (C_2) y riego controlado por sensores de matriz granular (GMS_3). El objetivo del riego controlado por sensores fue mantener la humedad del suelo a un nivel pre-fijado para lo cual se emplearon las lecturas de los sensores de humedad del suelo, enterrados a una profundidad de 0.15 m en la zona radicular del cultivo. El sistema ejecutaba hasta 8 eventos de riego por día de hasta 20 minutos cada uno. Para controlar el movimiento del agua se instaló un sensor de humedad adicional a una profundidad de 0.50 m. El consumo de agua se midió utilizando un caudalímetro en cada una de las parcelas experimentales. El consumo final de agua en L/m2 fue de 589,6 para el ET_1; 532.1 para C_2 y 530.3 para GMS_3. El rendimiento comercial fue similar en los tres tratamientos: 121.9 para ET_1; 126.5 para C_2 y 116.9 para GMS_3 (en Mg/ha). Los valores de humedad en ambas profundidades del ET_1 se mantuvieron cercanos a la capacidad de campo durante toda la campaña; excepto por un período de 30 días durante la etapa de máximo crecimiento donde, a 0.15 m, se observaron valores menores. El riego basado en sensores mantuvo la humedad del suelo del horizonte superior en las cercanías de los límites marcados alcanzándose valores mayores tras lluvias. A 0.5 m de profundidad, el tratamiento C_2 mostró un comportamiento similar al ET_1 mientras que el GMS_3 mostró cómo el perfil de suelo se secaba lo que se tradujo, muy probablemente, en una reducción del agua de riego empleada. Finalmente se discute el interés del empleo de sensores de humedad desuelo para mejorar el método Penman-FAO aprovechando las reservas de agua existentes en el suelo.

ABSTRACT. To evaluate the use of soil moisture sensors to control irrigation in a processing tomato crop (*Lycopersicum esculentum*, Mill) planted on a clay-loamy soil, three different types of irrigation scheduling were used: irrigation calculated according to the ETc (ET_1), irrigation controlled by capacitance soil moisture sensors (C_2) and irrigation controlled by granular matrix sensors (GMS_3). Irrigation controlled by sensors maintained soil moisture at a set level using a soil moisture sensor, buried at a depth of 0.15 m within the crop root-zone. The system allowed up to 8 irrigation events per day of 20 minutes each. In order to monitor water movement an additional sensor was installed at a depth of 0.50 m. Water consumption was also measured by using water-meters in each of the experimental plots. Water consumption (in L/m2) was 589.6 for the ET_1; 532.1 for the C_2 and 530.3 for the GMS_3. Total marketable yields were similar for all treatment: 121.9 for ET_1, 126,5 for C_2 and 116.9 for GMS_3 (in Mg/ha). ET_1 soil moisture readouts showed values at or close to field capacity for the whole season, at both depths; except for a 30 days period during maximum growth when lower values where observed at 0.15 m. Sensor based irrigation maintained water content in the upper profile around the set threshold reaching higher values after rainfall events. At 0.5m depth, C_2 showed a very similar behaviour to ET_1 whilst GMS_3 showed a dessication pattern after the initial stages of the crop which was very likely translated in an overall reduction of the water consumption. Finally the interest of the use of soil moisture sensors to enhance the Penman-FAO method through the use of water reserves from the soil is discussed.

1.- Introduction

Water resources are scarce and incorrect irrigation management can cause both economical losses and damage to the environment by nutrient leaching from the soil surface to the groundwater. Good agricultural practices must include both the knowledge of the water usage by the crop and techniques that permit an efficient irrigation management.

One of the techniques that allows an efficient irrigation is drip irrigation which makes a localized, high-frequency, low-volume irrigation possible, thereby reducing both water loss and crop water stress. When drip irrigation is used rationally in conjunction with irrigation scheduling techniques, it is possible not only to save water, but also to minimize the risk of nutrient leaching, mainly nitrogen, thus reducing the impact of agriculture on belowground water.

There are various methodologies that provide the necessary information to determine an optimum irrigation schedule. Water balance is the most commonly used, others are based on the determination of the crop's water requirements, the knowledge of plant water status or the determination of crop-available soil water. Greenwood et al. (2010) carried out a review of different methods that may improve irrigation efficiency.

Thanks to their relative low cost, it is nowadays feasible to install and use probes that, through indirect means, give a real-time knowledge of soil moisture content. Coupling these devices with other irrigation components, irrigation events can be triggered according to predetermined thresholds thus applying water to the crop when the soil moisture is under a certain level. Systems based on this principle have been used in different horticultural crops such as peppers (Dukes, et al. 2003), tomatoes (Muñoz-Carpena et al., 2003), zucchini (Zotarelli et al. 2008), onions and potatoes (Shock et al. 2002). In general, these studies show that these methods allow a higher water use efficiency and reduce nitrate leaching.

There are detailed reviews, such as the one written by Charlesworth in 2005, covering different systems used to determine soil moisture content. Within those, some of the cheapest and most widely available options are capacitance sensors and granular matrix sensors (GMS). Both types of sensors are low cost and require little or no maintenance. In a previous experiment to compare the responses of these two types of sensor in two different soils (Huete, et al., 2010), loam and sandy-loam, GMS worked well in the range of -0.010 to -0.065 MPa regardless of soil type. In the same experiment capacitance sensors showed a good response in the whole soil moisture range, from saturation to permanent wilting point, nevertheless they were also heavily affected by the heterogeneity of the soil due to the limited scope of their measurements. Therefore the use of their readouts in Volumetric Water Content (VWC) for comparison between sensors or their calibration is difficult.

The objective of this study was to evaluate the use of capacitance and GMS soil moisture sensors for automatic high frequency drip irrigation in processing tomato in the Ebro valley (Spain) comparing it to a well known strategy based on crop evapotranspiration.

2.- Material and Methods

The experiment was conducted during the 2010 growing season at the La Rioja AgriFood Research and Development Center located in the central Ebro valley. The soil was a clay-loam classified as haplocalcic vertic, acuic, fine, mixed, mesic (S.S.S.-USDA, 2006).

A tomato crop (*Lycopersicon esculentum* Mill, *var. Frigio)* was grown on a soil mulched with black polyethylene film 0.015 mm thickness. The experimental design was a randomized complete block with three drip-irrigation treatments **ET_1**, **C_2** and **GMS_3** and three replicates each. Each elemental plot consisted of 3 crop beds, each 15 m long, 0.9 m wide and 0.1 m high, spaced 1.6 m from centre to centre, covering a total area of 72 m^2. A drip line with emitters every 0.2 m and a flow rate of 1 $L \cdot h^{-1}$ at 55 kPa was buried at a depth of 0.05 m under the centerline of the soil beds. A water meter was installed at the head of each replicate to monitor water consumption.

Two soil moisture sensors were installed in each replicate at 0.15 and 0.50 m depth both at a horizontal distance of 0.10 m from the drip line. All sensors were connected to a CR10X (Campbell Scientific International, Logan, UT, USA) datalogger. In the C_2 and GMS_3 treatments the top sensor was used to control irrigation scheduling. The bottom sensor was used to understand water consumption throughout the soil profile. In the ET_1 irrigation treatment two sensors of each type (Capacitance and GMS) were installed to monitor soil water content and allow comparisons with the C_2 and GMS_3 treatments.

Irrigation was set as defined below:

a) ET_1: irrigation based on the ETc-dual crop coefficient method (Allen et al., 1998). Scheduling was set by distributing the daily irrigation goal dosage between different irrigation events of 10 to 20 minutes each. The number of irrigation events varied from 2 to 8 per day according to the crop needs throughout the season.

b) C_2: Irrigation controlled by capacitance soil moisture sensors, ECH$_2$O-10HS (Decagon; Pullman, WA, USA). Irrigation was triggered when the averaged Relative Extractable Water (REW) was lower than a set threshold. From day of year (DOY) 152 to 212 threshold was set at 85% of REW and from DOY 212 until the end of the irrigation 70% of REW. Up to 8 irrigation events were carried out daily. Irrigation events were of 10 minutes each up to DOY 181, 15 min. up to DOY 196 and 20 min. from DOY 197 onwards.

c) GMS_3: Irrigation controlled by granular matrix sensors, Watermark (Irrometer; Riverside, CA-USA). Irrigation events were triggered when the averaged value for the top sensor of the 3 replicates was lower than -0.025 MPa. Threshold was maintained constant during the season. The maximum number of irrigation events per day and their duration was the same as explained for the C_2 treatment.

In the C_2 treatment REW was used instead of VWC. This transformation was carried out since according to previous results (data not published) readouts from the sensors, expressed in VWC, when the soil was at a similar soil moisture level were different and changes in soil moisture content implied changes of different amplitudes in the VWC sensor readouts. Measurements were then normalized according to the following expression proposed by Granier (1987):

$$\text{REW (\%)} = \frac{VWC_{actual} - VWC_{permanent\ wilting\ point}}{VWC_{field\ capacity} - VWC_{permanent\ wilting\ point}} \cdot 100$$

VWC values at field capacity and permanent wilting point were defined for each sensor in the initial stages of the crop. $VWC_{field\ capacity}$ was defined graphically when excess water was applied studying the hourly readouts from the sensors and looking at the stabilization values after the excess water had drained to the sub-soil. $VWC_{permanent\ wilting\ point}$ was defined through laboratory analysis. Soil samples were taken and gravimetric soil moisture was obtained and then transform to VWC by the apparent density. The REW of the samples was calculated theoretically using the soil texture into equations provided by Saxton et al (1986). Using REW, $VWC_{field\ capacity}$ and the readouts from the sensors when the sample was taken it was possible to calculate $VWC_{permanent\ wilting\ point}$

On May the 12th (DOY 132), beds were planted with a single row of tomato plantlets at a distance of 0.05 m from the drip line. The plantlets were spaced 0.2 m apart equivalent to a plant density of 31,250 plants·ha-1. All plots were fertilized with the same amount of N, P and K. Following transplant and to assure the establishment of the plantlets, excess water was applied to all treatments. C_2 received around 30 L/m^2 less than the other two treatments in this initial stage. On DOY 152 the different irrigation strategies were set out.

On DOY 233 and for 2 additional days irrigation events could not be carried out due to the failure of the pumping system. As a consequence the C_2 treatment failed to irrigate for an additional two days. As a result, during this period, ET_1 and GMS_3 applied, respectively, 11.82 and 13.16 L/m^2 more than C_2.

For all treatments, irrigation was stopped on DOY 243 and harvest was carried out on the 6th of September (DOY 249) when 80% of the fruit was ripe. Tomatoes were collected along 6 m of the beds (covering a total area of 9 m^2) at each of the replicates. Total and marketable productions were recorded. Water use efficiency related to marketable yield (WUEy) was calculated for each plot as the ratio between marketable yield and water applied by irrigation. Rainfall accumulated during the crop period was 83 L/m^2.

The results were analysed statistically using a two-way ANOVA test. When a significant F-value was detected, comparison of means was carried out by the Tukey test.

3.- Results and discussion

As shown in table 1, marketable yield and fruit weight were similar and statistical differences were not found between treatments. ET_1 irrigation scheduling resulted in a significantly higher volume (≈10%) of water applied as compared to the other treatments. No significant differences were found in water use efficiency (WUEy). Zotarelli et al (2008) found similar results tough in their case WUEy did show also statistical differences. The relatively low differences in water applied between ET_1 and C_2, GMS_3 treatments could be attributed to the fact that ET_1 treatment was already well optimised, irrigation dosage was changed daily to accommodate it to the ETc demand and up to 8 irrigation events were set.

Fig. 1 shows the water applied for the three different treatments. After irrigation was set out according to the different strategies, GMS_3 consumed water at a slower rate than the other two treatments and, from DOY 203 up to the end of the crop period, was the least irrigated treatment. In the initial stages C_2 consumed water at the highest rate getting very close to ET_1 values on DOY 210. Soon after that, irrigation threshold for this treatment was changed and water consumption in relation to ET_1 diminished. ET_1 was the most irrigated treatment throughout the season and from DOY 210 onwards its rate of water consumption remained the highest. After the unexpected irrigation stop on DOY 233 C_2 and GMS_3 values became similar and differences in final water consumption between both treatments were negligible. It is unclear how the final results would have been affected had this event not happened.

Table 1. Total and marketable crop yield, water applied by irrigation and water use efficiency related to marketable yield (WUEy) for tomato crop. Mean followed by different letters indicates significant differences according to the Tukey test ($\alpha \leq 0,05$). ns not significant; * significant p<0,05; ** significant p<0,01; *** significant p<0,001.

Treatm.	Total yield (Mg/ha)	Marketable yield (Mg/ha)	Marketable yield (g/fruit)	Irrigation + rainfall (l/m^2)	WUEy (kg/ha/m^3)
ET_1	145,4	121,9	58,0	589,6 a	24,6
C_2	146,9	126,5	57,2	532,1 b	28,9
GMS_3	140,2	116,9	53,9	530,3 b	26,8
	ns	ns	ns	**	ns

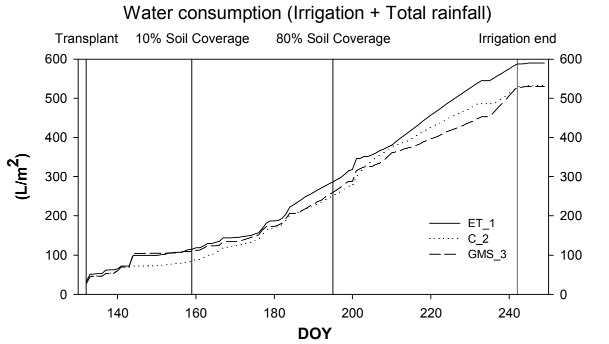

Fig. 1. Water consumption per treatment expressed in L/m^2 as a result of irrigated water and rainfall.

3.1.- Analysis of soil moisture evolution in each of the treatments

ET_1 treatment, Capacitance readouts (Fig. 2): Soil moisture readouts, both at 0.15 and 0,50 m depth, showed values at or close to field capacity (100% REW) in the initial stages of the crop up to DOY 170. After that point sensors at 0.15 m showed several fluctuations surpassing field capacity after rainfall events and well below field capacity outside those events. Water content in this horizon was not stable during the maturation period and between DOY 210 and 225 and REW values increased. On the other hand, after DOY 170, sensors located at 0.5 m fell below field capacity for five days and, after some rainfall events, reached soil saturation again on DOY 179 staying there until DOY 196. After that day sensor readouts showed a subtle drying pattern.

ET_1 treatment, GMS readouts (Fig. 3): Soil moisture readouts at 0.15 m showed a constant output up to DOY 170. After that and for 2 fifteen-days periods during maximum growth (DOYs 170 to 184) and early maturation (DOYs 194 to 210) lower values where measured, getting close but never surpassing -0.025 MPa. From DOY 210 readouts showed values at or over -0.010 MPa until the pumping malfunction event on DOY 233 where values rapidly decreased and, after irrigation was resumed, were almost constant up to the irrigation end. Readouts from sensors at 0.5 m showed a constant output over -0.010 MPa for the whole season up to the irrigation end.

As expected, GMS (Fig. 3) showed a certain degree of inertia in its measurements when compared to capacitance sensors readouts (Fig. 2). Also from measurements at 0,5 m depth we can conclude that the plant did not use a large quantity of the water stored in the deeper horizons. This can be explained by a lack of roots in the deeper horizons since the crop found the necessary water in the upper profile of the soil (Ibáñez, 2011).

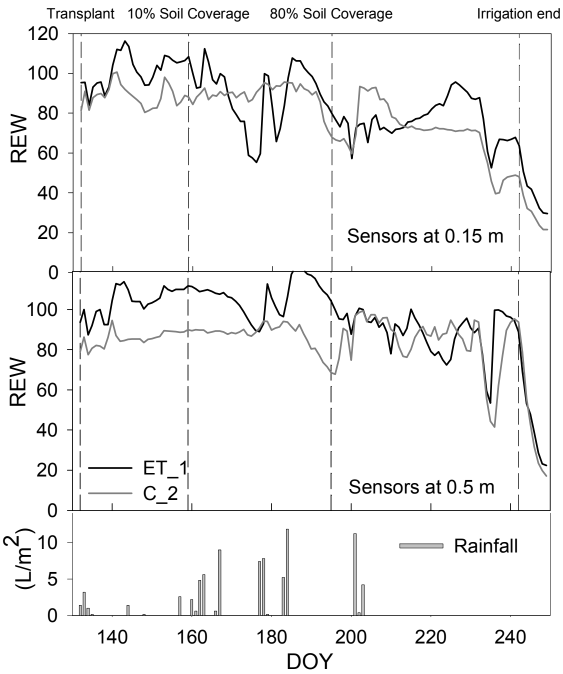

Fig. 2. C_2 vs ET_1 treatment comparison and rainfall.

C_2 treatment, Capacitance readouts (Fig. 2): At 0.15 m soil moisture was close or at soil saturation up to DOY 152 when the irrigation strategy started and REW values descended to the irrigation threshold, 85% of REW. Soil moisture levels were maintained afterwards with little variations due to rainfall. From DOY 193, a period where soil moisture was lower than usual occurred which prompted us to extend the time of the irrigation events to 20 minutes on DOY 197. Soil moisture levels increased soon afterwards due to the rainfall, reaching values close to field capacity. From DOY 212 sensor readouts stabilized around the 70% of REW threshold until DOY 233. Although irrigation was resumed on DOY 238 the targeted soil moisture could not be reached again before irrigation cutoff. In the 0.5 m horizon soil moisture remained stable between 80% and 100% of REW for the most part of the season until DOY 233. When irrigation was resumed soil moisture values at this depth recovered before irrigation was stopped. It seems possible that due to the soil characteristics after the soil dried out irrigation water drained from the upper to the lower profile thus explaining the differences in soil moisture between the two depths.

GMS_3 treatment, GMS readouts (Fig. 3): After the initial, post-transplant-irrigation period and when rain events did not increase soil humidity, readouts from sensors installed at 0.15 m depth were at or around -0.025 MPa except from a larger excursion between DOYs 235 and 243 where values were lower, reaching a minimum of -0.040 MPa for a day. These values are consistent with the irrigation scheduling strategy for this treatment. The subtle variations around the threshold level could be explained by the variation of the sensor's readouts throughout the day, due to the scheduled irrigation pattern. Sensors at 0,50 m depth maintained a constant readout, at or close to soil saturation, up to DOY 176 when the profile started to dry out. The desiccation pattern in the lower horizon was also affected by rain events and remained above -0.050MPa until DOY 234 when readouts were severely affected by the lack of irrigation and sensors went out of their working limits. Water available between 0.01 and 0.04 MPa was estimated to be around 40 L/m^2. From the available data it seems that the plant used the water of the deeper horizons effectively reducing the use of irrigation water.

The increase in the irrigated water in the last days of the crop cannot be properly explained and could be due to the effect of the sudden lack of irrigation or to an increased demand on the side of the plant in the late maturation period due to the exhaustion of the available water in the lower horizon.

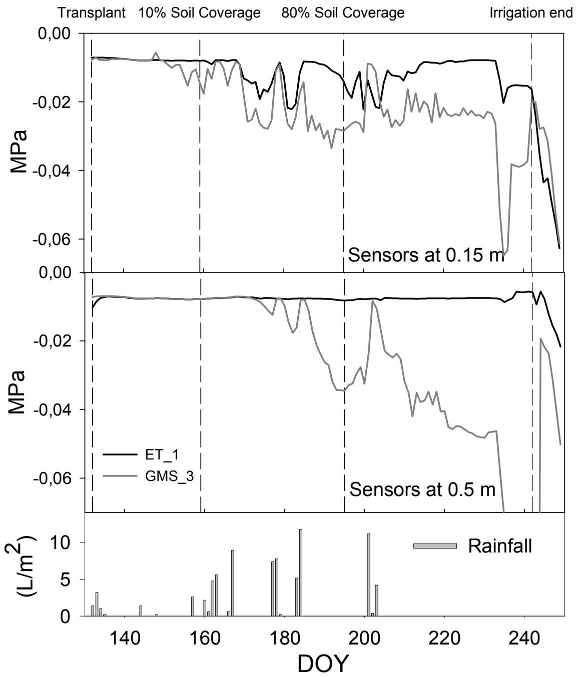

Fig. 3. GMS_3 vs ET_1 treatment comparison and rainfall.

4.- Conclusions

From the results it seems possible to enhance the Penman-FAO method by combining it with the use of soil moisture sensors. A reduction in the applied water could be obtained by setting the start of the irrigation season, after the post-transplant irrigation, according to the readouts of soil moisture probes. Also it seems feasible to stop irrigation a few days earlier, in the last days of the crop period, taking advantage of the water stored in the soil profile.

After looking at the data gathered from this experiment it seems that GMS sensors are easy to use, they did not need conversions or calibrations in order to set irrigation thresholds and, within the optimum soil moisture range for horticultural crops, they offered good measurements. On the other hand capacitance probes seemed to work well but we found difficulties when adjusting the readouts of the probes. We overcame this problem through an intensive use of laboratory analysis. Farmers could face similar difficulties when defining their irrigation scheduling without prior knowledge of their sensor response after installation. Because of this, and in order to consider capacitance probes as an option for irrigation scheduling in horticultural-non perennial crops, an alternative protocol should be designed.

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