DEVELOPMENT OF A DSS BASED ON SOIL MOISTURE SENSORS TO IMPROVE FERTIGATION EFFICIENCY. A POMEGRANATE CASE STUDY

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Abstract

In arid and semi-arid areas, there is a need to look for technologies that increase water use efficiency and make available additional water sources for fertigation, decreasing water scarcity and the discharge of water and nutrients to the environment. Specifically, one of the main crops in the Region of Murcia is the pomegranate, which can be affected by water scarcity if a correct irrigation strategy is not applied. For thus, the main objective of this work is the development of a decision support system (DSS) to manage the irrigation on a pomegranate field, based on the interpretation of the soil water content at different depths provided by soil sensors. A field experiment was carried out during 2021 and 2022 seasons. During the first season, different deficit irrigation treatments were applied to explore crop responses to the timing and the regime of the irrigation applications and during the second season, the PRECIMED-CEBAS DSS has been developed and it is being evaluated, comparing it against the irrigation provided by a traditional irrigation protocol. Two deficit irrigation treatments with both irrigation protocols are also being compared.

1 Introduction

In the context of climate change, the problem of water scarcity for agriculture has been accentuated during the last years. In this sense, Mediterranean countries are increasingly looking for more innovative irrigation approaches, not only to cope with water scarcity and policies involving greater use of water, but also to satisfy the needs of the farmers and the demands of the consumers.

Pomegranate plants cope with water stress developing stress avoidance and stress tolerance mechanisms and they are considered as a drought-resistant crop (Rodríguez et al. 2012, Galindo et al. 2014a), however when they are produced with commercial purposes, they require regular irrigation along the season, especially in arid or semiarid areas, in order to achieve optimal yields with high quality fruits (Holland et al. 2009) and to reduce fruit physiopathies, as fruit cracking and splitting (Galindo et al. 2014b, Griñán et al. 2019). In this last respect, deficit irrigation strategies might play an important role for pomegranate production in Mediterranean countries, improving water use efficiency at farm level and complementary reducing nutrient loss from the root zone (Galindo et al., 2017). However, some situations such as a rapid increase of temperature when low amount of irrigations are applied can difficult the task of maintaining the plant water status, resulting on yield losses or diminishing fruit quality. Therefore, it is of great importance to set the appropriate deficit irrigation strategy applied to this crop. This way, the use of plant-based water status indicators might predict crop performance under a given irrigation scheduling regime, since plant water status controls several physiological processes and crop productivity.

Conventional irrigation scheduling based on soil water measurements has some weaknesses such as: it requires good knowledge of root distribution and relative density; for irrigation scheduling procedures involving high-frequency irrigation systems, information about crop evapotranspiration (ET_c) is required); in young tree plantations, empirical factors in the estimation of ET_c are needed; and water needs of some woody crops of increasing interest in the Mediterranean region have not been still determined. Also, the increasing worldwide shortages of water and costs of irrigation are leading to an emphasis on developing new methods of accurate irrigation scheduling and control that minimize water and nutrient use efficiency. In recent years there has been a wide range of proposed novel approaches to irrigation scheduling which have not yet been widely adopted; many of these are based on modern and precise soil-plant sensors (Ortuño et al. 2010). In this sense, the use of sensors that measures the soil water status is a key complement to modulate the water requirements of the crops. Soil variables, such as soil moisture content or soil matric potential, are considered by many authors as crucial part of scheduling tools for managing irrigation (Cardenas-Lailhacar and Dukes, 2010; Soulis et al., 2015). However, on their own, these devices imply certain limitations: they require a large number of sensors and the information reported does not offer a factual understanding of water and nutrient balance within water-soil-plant system.

For these reasons, this work proposes an automated decision support system (PRECIMED-CEBAS DSS) to manage the irrigation on a pomegranate field, based on an irrigation scheduling protocol based on the interpretation of the soil water content at different depths provided by soil sensors.

To do this, during the first season, different deficit irrigation treatments were applied in order to explore crop responses to the timing and the regime of the irrigation applications. During the second year, the PRECIMED-CEBAS DSS has been developed and it is being evaluated by comparing it against the irrigation provided by a traditional irrigation protocol. Two deficit irrigation treatments with both irrigation protocols are also being compared.

2 Materials and methods

2.1 Plant material and experimental conditions

The experiment carried is conducted in a pomegranate tree orchard located at the CEBAS-CSIC experimental field-station in Murcia, Spain (38° 6'N, 1° 2'W). It started in the season of 2021 and it continues during this growing season 2022.

The plant material was own rooted fifteen-year-old pomegranate trees (*P. granatum* (L.) cv. Mollar de Elche) in a 3 m × 5 m spacing pattern and the total area cultivated is 0.8 ha. The sandy clay loam soil of the experimental site is characterized by a high stone content (39% by weight) and a bulk density of 1.37 g/cc. The volumetric soil water content at saturation, field capacity and permanent wilting point is 49, 29 and 18%, respectively. Irrigation water has an electric conductivity of 0.8–1.0 dS m^{-1}.

Pest control and fertilization practices were those usually used by local growers, and no weeds were allowed to develop within the orchard. The pomegranate trees have only one trunk. They are lightly pruned every year and sprouts and suckers are removed as they appear, in order to encourage fruit production.

2.2 Irrigation treatments

Irrigation takes place by mean of a drip irrigation system, with one lateral pipe per tree row. The emitters are spaced 50 cm (six per tree) and they deliver 2.2 L h^{-1}.

During the first season (April-October 2021), four treatments were applied in order to explore crop responses to the timing and the regime of the irrigation applications:

- Control, C, irrigation was set at 120% of the estimated crop evapotranspiration (ET_c) avoid limiting soil water conditions. ET_c was calculated as a product of the reference evapotranspiration (ET_0) and crop coefficient (K_c). ET_0 was calculated using the Penman-Monteith formula (Allen et al.1998) and the K_c values reported were based on results reported by Intrigliolo et al. (2011).
- SDI, where water was applied at 50% of the water requirements of the crop through the whole season.
- RDI_{fg}, where irrigation was applied at 50 % of the water requirements of the crop during July and August (linear fruit growth phase) while the rest of the season 120% ET_c was applied.
- RDI_r, where irrigation was reduced a 75 % of the water requirements of the crop during the ripening phase (three weeks before harvest) while the rest of the season 120% ET_c was applied.

During the second year (April-October 2022) the irrigation treatments have been modified, and the four treatments are as follow:

- Control, C, irrigation is scheduled to replace 100% of the ET_c.
- SDI, where irrigation is applied at 50% of the Control treatment through the whole season.
- $C_{PRECIMED}$ treatment, where the plants were irrigated according to the PRECIMED-CEBAS protocol (described in 2.3 section).
- $SDI_{PRECIMED}$, where irrigation is applied at 50% of the $C_{PRECIMED}$ treatment during through the whole season.

2.3 Irrigation protocol

PRECIMED-CEBAS protocol is developed on the frame of the Project. It is based on the information recorded from the multi-layer Drill and Drop soil probes installed on the farm. These probes are recording the volumetric soil water content (θ_v) at different depths (10, 20, 30, 40, 50 and 60 cm) every 15 minutes, measurements monitored in real time through the PRECIMED platform and used as a control system variable.

In order to schedule irrigation, we are focused in two specific depths (40 and 60 cm, level 4 and 6, respectively), based on the evidence that for drip irrigated woody crops, the more active roots are located in the first 50 cm of the soil profile (Intrigliolo et al. 2012). The information obtained from the soil probes is used to guarantee that soil water content is maintained in an optimum range between these two levels, avoiding the drainage at level 6 and ensuring an appropriated and constant soil moisture at level 4 with every daily irrigation event. For it, we are following the dynamics of the soil moisture on these levels after each irrigation event and acting according to their results. At the moment, we are doing this operation manually, but the automation of the irrigation based on the results of the protocol is under process, and it is expected that it responds to the commands detailed below.

In order to automate the irrigation protocol, the system (PRECIMED platform) needs to know if soil moisture after irrigation is higher than before starting irrigation, in level 4 and level 6.

According to the results, the system should execute the following commands:

In level 4 (40cm depth):

$A_{40} – B_{40} > 1$* → This means that water reached level 4, so irrigation is maintained

$A_{40} – B_{40} < 1$ →This means that water didn't reach this level, so irrigation time is increased in a 15% for the next day.

Where A_{40} stands for the absolute value of the moisture level at 40cm one hour after the first irrigation event of the day ends and B_{40} is the value of the moisture level when the first irrigation event of the day starts.

In level 6 (60cm depth):

$A_{60} – B_{60} \geq 0.3$* → This means that water reached level 6, so irrigation is reduced for the next day in a 15%.

$A_{60} – B_{60} < 0$ → This means that water did not reach level 6, so there is no water drainage of the more active root zone.

Where A_{60} stands for the absolute value of the moisture level at 60cm two hours after the first irrigation event of the day ends and B_{60} is the value of the moisture level when the first irrigation event of the day starts.

*At the beginning of the season, several tests were done in order to establish the minimum variations that the results have to report to increase or decrease the irrigation timing. Thereby, a 15% of the settled time was considered as an appropriate value to both actions, increase the irrigation time when water did not reach level 4 or decrease it when water reaches level 6.

There are some premises that the protocol follows:

- Season starts with one hour irrigation per day.
- Irrigation events should be larger than 60 minutes and shorter than 240 minutes
- When the timing exceeds 240 minutes, set 2 irrigation events per day
- Calculations are done two hours after irrigation ends.

This way, the sensor at level 4 will tell us how much irrigate, and the sensor at level 6 when irrigate.

2.4 Measurements

2.4.1. Environmental conditions

Agro-meteorological data were recorded by an automated weather station located in the CEBAS-CSIC experimental field station, which reads the values every 5 min and recorded the averages every 15 min. From these data, reference crop evapotranspiration (ET_0) was calculated hourly using the Penman-Monteith equation (Allen et al., 1998).

2.4.2. Soil water status

Soil humidity is registered by the PRECIMED platform in four points of the farm and at different depths (10, 20, 30, 40, 50, 60 cm) through Drill and Drop soil probes, allowing its monitoring at real time. These sensors have been deployed and connected thanks to the use of CPS gateways with wireless communication to the platform.

In addition, 24 fully integrated digital TDR soil moisture sensors (TDR-315H) register soil moisture at 20 and 40 cm depth. The sensors were connected to two dataloggers (model CR1000 with AM16/32 multiplexer, Campbell Scientific Ltd., Logan, USA) and programmed to report means every 30 minutes.

2.4.3. Plant water status

Plant water status was periodically evaluated throughout the growing season by measuring midday stem water potential (Ψ_{stem}) using a pressure chamber (Soil Moisture Equip. Corp. Model 3000, 153 Santa Barbara, CA, USA). Measurements were taken at around 12 h solar time in fully expanded leaves selected from near the tree trunk in the north-facing part of the tree. The leaves were covered with aluminum foil bags for at least 2 h prior to the measurements. Four leaves per treatment were used.

Leaf gas exchange measurements were made on the same days as Ψ_{stem}, at around 11:00 h solar time, in one sun-exposed leaf per replicate and four replicates per irrigation treatment. The net photosynthesis (P_n) and stomatal conductance (g_s) were measured with a field-portable closed photosynthesis system (LI-COR, LI-6400, Lincoln, NE, USA).

Leaf temperature (T_c) were measured manually with a thermal imager (ThermaCam FLIR-e50 System, Inc., Danderyd, Sweden). Infrared images were taken periodically from the sunlit side of the canopy in four plants per irrigation treatment at midday throughout the experiment and in a constant distance of 0.5 m. Crop water stress index CWSI = $(T_{dry} - T_c)/(T_{dry} - T_{wet})$ (Idso, 1982) was calculated, being T_{dry} and T_{wet}, leaf temperature at minimum and maximum transpiration, respectively.

2.4.4. Yield

Pomegranate fruits were harvested at commercial maturity on 1–2 harvesting days starting at the beginning of October 2021. Yield and efficiency parameters were measured in all the experimental trees. Total yield was weighed with an electronic scale, and the number of fruits per tree was counted. Fruits affected by cracking were also considered in the study. Average fruit mass was calculated from total mass and number of fruits per tree. In addition, fruit size was also calculated in 10 fruits per replication.

2.4.5. Statistic

The design of this experiment was completely randomized with three replications per treatments. Three adjacent eleven tree rows were used per each replication. The inner plants of the central row of each replica were used for measurements, whereas the other plants served as border plants. The data were analysed by one-way ANOVA using Statistical Package for the Social Sciences (IBM SPSS Statistics 26 for Windows). Treatment means were separated with Duncan's Multiple Range Test ($P \leq 0.05$).

3 Results and discussion

3.1. Plant response to different irrigation strategies

During the 2021 experimental period, θ_v values were high and constant (around 35%) in the control treatment (C). θv in SDI and RDI_{fg} plants decreased from the outset of the experiment, reaching minimum values of around 18% at the end of the stress period. After rewatering the RDI_{fg} plants, θv values rose. Soil moisture dropped sharply in treatment RDI_r when irrigation was reduced to 25% ETc, reaching minimum values (Fig. 1).

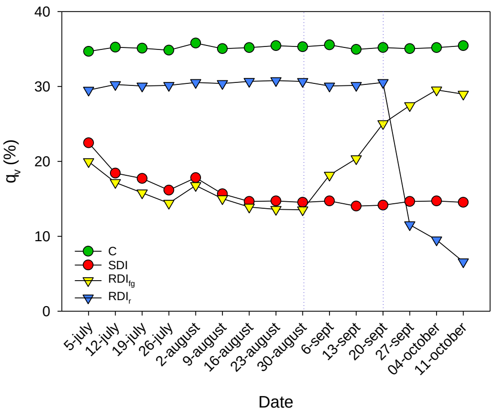

Fig. 1. Volumetric soil water content (θ_v) in Control (green circles), SDI (red circles), RDI_{fg} (yellow triangles) and RDI_r (blue triangles) treatments during the 2021 experimental period. Vertical dotted lines indicate the change of irrigation in the different irrigation treatments.

The water status of C plants remained in good conditions as shown by the high and almost constant Ψ_{stem} values during the experimental period, whereas deficit irrigation treatments induced a reduction of Ψ_{stem} in the stress periods. Specifically, SDI and RDI_{fg} plants showed a significant Ψ_{stem} decrease shortly after reducing the irrigation. However, while SDI maintained low values for almost the entire trial, RDI_{fg} recovered them after summer, when irrigation was restored to 120% ET_c. Ψ_{stem} of RDI_r drop to minimum values just after irrigation reduction (Fig. 2a). In any case, Ψ_{stem} values didn't decrease below -1.7 MPa, suggesting a moderate water deficit situation (Galindo et al. 2014b).

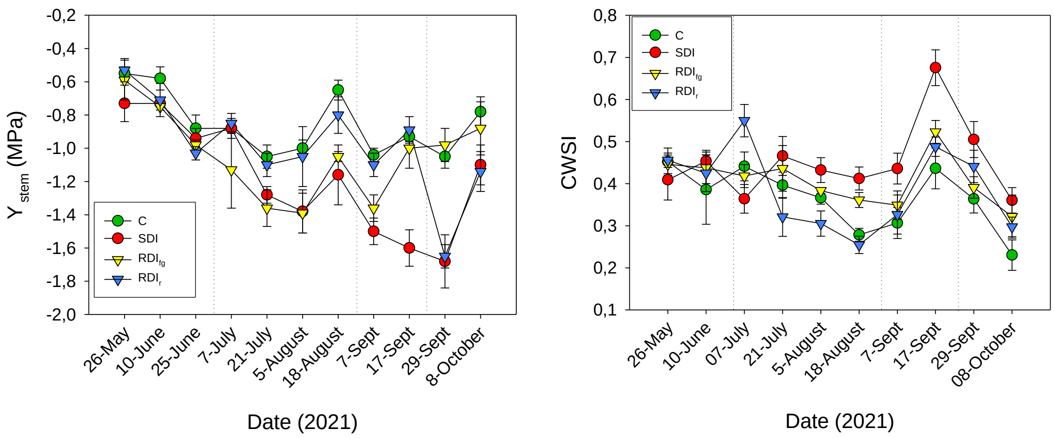

Fig. 2. Stem water potential (Ψstem) (a) and crop water stress index (CWSI) (b) values (mean ± SE) for pomegranate plants in Control (green circles), SDI (red circles), RDI_{fg} (yellow triangles) and RDI_r (blue triangles) treatments during the 2021 experimental period. Vertical dotted lines indicate the change of irrigation in the different irrigation treatments.

Thermal images detected differences in water status between control and water stressed plants. Crop water stress index (CWSI) in deficit irrigation treatments tended to be above the control values at the end of each stress period, being the highest values those corresponding to SDI plants (Fig. 2b), corroborating the worst water status of these plants. In addition, the relatively accurate relationship found between CWSI and Ψ_{stem} (data not shown) confirms the use of CWSI as a good indicator of crop water status, according to García-Tejero et al., 2018.

In general, the deficit irrigation treatments did not produce a significant effect in the quantity and quality of the yield (Table 1), only a significant effect on the average weight of the fruit was observed, where the lowest values were obtained in SDI and RDI_{fg} treatments. However, a tendency to increase the non-marketable yield of treatments SDI was observed which could be due to cracking caused by water stress (Matthews and Shackel, 2005).

Table 1. Yield and fruit quality of the pomegranate fruits for the different irrigation treatment at harvest (October 2021).

	C	SDI	RDI_{fg}	RDI_r
Kg fruit tree^{-1} marketable	45,44	31,12	39,49	41,65
No. Fruits tree^{-1} marketable	135,38	93,89	114,56	108,11
Kg fruit tree^{-1} non-marketable	3,70	8,78	4,44	6,54
No. Fruits tree^{-1} non-marketable	20,63	42,67	25,67	32,89
Mean fruit weight (kg)	0,36 ab	0,33 b	0,34 b	0,39 a
Fruit equational diameter (mm)	85,35	87,96	89,40	87,11
Fruit height (mm)	76,42	75,73	78,80	75,59

3.2. Evaluation of the PRECIMED-CEBAS DSS

During the 2022 season, the PRECIMED-CEBAS DSS is being evaluated. Similar values of water potential and stomatal conductance are observed between C and $C_{PRECIMED}$ plants, as well as between SDI and $SDI_{PRECIMED}$ plants (Fig. 3), indicating an adequate irrigation protocol.

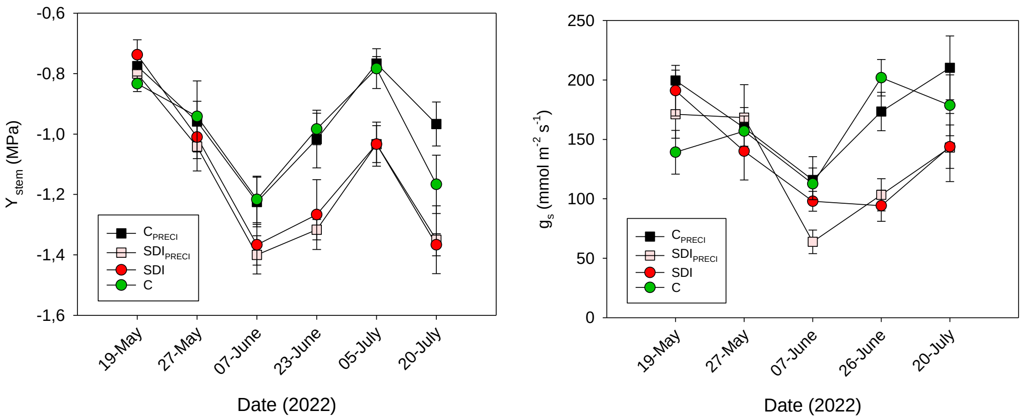

Fig. 3. Stem water potential (Ψstem) and stomatal conductance (g_s) values (mean ± SE) for pomegranate plants in Control (green circles), SDI (red circles), SDI_{PRECI} (yellow squares) and C_{PRECI} (black squares) treatments during the 2022 experimental period.

Anyhow, according to the last measurement of Ψ_{stem} and g_s carried out from mid July 2022, treatments C and $C_{PRECIMED}$ show certain variation, being $C_{PRECIMED}$ the one which shows a better plant water status. This might be explained for the increase of the irrigation volume dependent on the constant monitoring of the volumetric soil water content, which has been greater than the treatment based on the ET_c. under remarkable conditions of very high evaporative demand. Actually, following the protocol, first day of July $C_{PRECIMED}$ was irrigated 189 minutes, and day 31st of July was irrigated 275 minutes, having an ascendant progression in almost the whole month, while Control treatment started the month with an irrigation schedule of 216 minutes per day, exactly the same timing that it has had for the last week of the month. In this way, as table 2 shows, during July 2022 $C_{PRECIMED}$ has received almost 250 m^3 ha^{-1} more than Control treatment, in other words it supposes about 1 hour more of irrigation per day, what might be decisive at this moment of fruit growth.

Regarding water consumption of both years, so far, we can observe, that in the most water demanding month of the year, July, $C_{PRECIMED}$ is the treatment with a higher demand, even higher than C_{2021} (Table 2). Nevertheless, looking at the graphs (Fig. 4) through PRECIMED platform and comparing the readings of the soil probes at different profiles, we can observe how in 2022, following the described protocol we are barely leaching any water, while in 2021 water drained to level 6 with every irrigation event after 7th July (day which start to be irrigated twice a day).

Table 2. Summary of water consumption for the different treatments of both years in the month July.

Treatment	**m^3 ha^{-1}**	**Season**
C_{2021}	1059	July 2021
SDI_{2021}	441	
C_{2022}	863	July 2022
SDI_{2022}	431	
$C_{PRECIMED}$	1102	
$SDI_{PRECIMED}$	551	

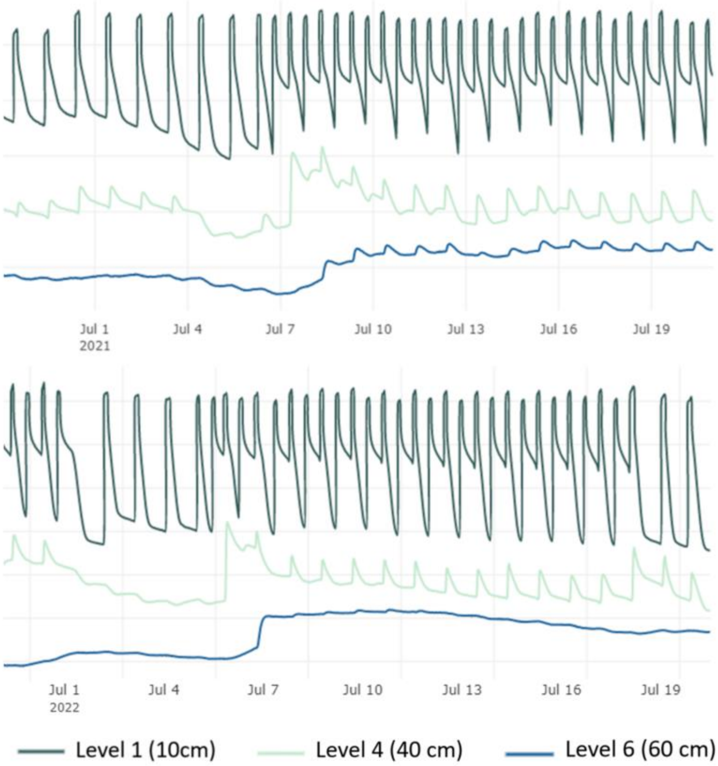

Fig. 4. Overview of the soil moisture sensors at three different depths in the visor of PRECIMED-CEBAS DSS. Above a period of 2021 season, below the same period but in year 2022.

4 Conclusions

So far, the different irrigation strategies are executed by the user through the PRECIMED platform, but it is expected that at the end of the project, the DSS will execute the irrigation programs according to the user convenience, triggering or stopping the electrovalves, and scheduling the irrigation in a more efficient way, either based on ET_0 criteria, capacitance probes or deficit irrigation.

PRECIMED irrigation protocol is also being validated. Some preliminary results could bring it in line with traditional irrigation approaches regarding water use efficiency. Although in the month showed in the results (July), the water consumption is higher than the treatment based on the ET_C, the combination with controlled deficit irrigation in no sensitive stages, is advisable to reduce water use without affect the production. In addition, it is important to know the response of the plants to this protocol throughout the 2022 season.

Although this study is being carried out in pomegranate trees, the approach used for irrigation might be easily replicated in other fruit trees.

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