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Differential irrigation scheduling by an automated algorithm of water balance tuned by capacitance-type soil moisture sensors

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ABSTRACT

Automated software tools are required to undertake the routine tasks and decision-making involved in scheduling irrigation. A key issue in this topic is how to integrate sensors in the scheduling approach. The objectives of this research were to test, in the context of drip-irrigated orchards: (a) the suitability of FAO's water balance method, locally adjusted by sensors, as the basis for the scheduling algorithm, (b) the suitability of capacitance-type soil moisture sensors, and an approach for their automated interpretation, for providing feedback to the scheduling algorithm, and (c) the performance of these combined approaches in the autonomous scheduling of irrigation in an apple orchard with heterogeneous vigour. The trial consisted of applying for two years the proposed approaches using an experimental web application, IRRIX, which scheduled irrigation of two irrigation sectors, which differed in tree size. The automated system was compared with manual scheduling by a classical water balance and with the actual evapotranspiration determined by a weighing lysimeter located in the same orchard. Results show that the irrigation applied by the automated approach in the sector of larger trees agreed with the ET determined by the lysimeter and, overall, with the scheduling by an experienced irrigator using a classical water balance. Meanwhile, as a result of a different feedback from soil moisture sensors, the same system reduced irrigation in the sector of smaller trees by a similar amount to that expected from the differences between the two sectors in the fraction of photosynthetically active radiation. This study illustrates that the method of water balance complemented with capacitance-type soil moisture sensors provides a sound basis for automated irrigation scheduling in orchards.

1. Introduction

At the plot level, an appropriate irrigation scheduling promote benefits such as saving water, decreasing environmental impacts and generating sustainable agriculture (Smith et al., 1996). In this context, the paradigm of precision irrigation emphasizes the variable-rate application of water according with the variability in weather, soil, crop properties and topography (Daccache et al., 2015). In practice, the variety of factors to take into account, together with the sequence of routine steps involved in scheduling irrigation, requires of farmers too much dedication, perseverance and expertise for conducting an optimized irrigation strategy. Consequently, digital tools are required to alleviate those requirements and enable commercial orchards apply precision irrigation with a feasible effort.

As a basis for determining the irrigation schedules, the most common method for calculating irrigation requirements follows the approach of FAO's soil water balance, where the water inputs in the soil-plant system are compared with the outputs (Doorenbos and Pruitt, 1977). The major output is the evapotranspiration by the crop (ET_C), which, under non-stress conditions, can be predicted from $ET_C = ET_O \times K_C$, where the evapotranspiration of a reference crop (ET_O) is estimated by the Penman-Monteith method and K_C is the crop coefficient characteristic of each crop (Allen et all., 1998). However, in horticultural crops, this approach can be quite uncertain since for a given crop species its K_C may vary with factors such as spacing and orientation of the rows (Intrieri et al., 1998), the plant variety (Higgins et al., 1992), crop load (Wünsche et al., 2000; Naor et al., 2008) and the size and shape of the canopy (Wünsche et al., 1995; Ayars et al., 2003; Girona et al., 2011; Marsal et al., 2014). In particular, the dependence of K_C on the solar radiation intercepted by the canopy has previously being studied in apple orchards (Girona et al., 2011; Auzmendi et al., 2011; Marsal et al., 2013). Furthermore, automated dosing of irrigation proportional to the daily amount of solar radiation intercepted by the canopy has experimentally been tested in apple (Casadesús et al.,

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2011). On the other hand, given the practical difficulties for a precise parameterization of the water balance, sensors can be used for an empirical site-specific adjustment. A simple approach is to set in the irrigation automata a general irrigation program, based on a conservative water balance and then, an automated system suppresses irrigation when the soil moisture exceeds a determined threshold (Muñoz-Carpena et al., 2005; Cáceres et al., 2008). A more elaborated approach is to determine irrigation doses by water balance but using the feedback from sensors for the empirical adjustment of Kc (Bacci et al., 2008; Casadesús et al., 2012). This combination of water balance and sensors sums up the ability to calculate irrigation volumes by water balance with the site-specific adaptive response to sensors.

The choice of the sensing method for providing feedback must trade-off its reliability with the feasibility of its usage in farms. One of the most widely used types of sensors for irrigation management are soil water sensors of capacitance type (Kojima et al., 2016; Bogena et al., 2017; Domínguez-Niño et al., 2019). Their functioning relies on the determination of the dielectric permittivity of the soil around the sensor, which mostly depends on the soil water content. Capacitance sensors have the advantage of being low cost and require little maintenance (Campbell, 1990; Kizito et al., 2008; Visconti et al., 2014). However, the response of these sensors varies with soil texture, presence of coarse elements, macropores, roots and soil compaction (Hignett and Evett, 2008). Furthermore, the dielectric permittivity is influenced by the temperature and by the electrical conductivity of the medium (Kizito et al., 2008; Kargas and Soulis, 2019). An additional complication in scenarios of localized irrigation is the heterogeneous distribution of soil water. In contrast with flood and sprinkler irrigation, where the water infiltrates on the most or all soil surface, in localized irrigation infiltration takes place directly in the area around the emitter (Cote et al., 2003; Irmak et al., 2016). This creates wet bulbs in the soil whose size and shape depend on many factors such as the soil hydraulic characteristics, the absorption by the roots, the evaporation from the soil surface, as well as the irrigation depth, relative position of the dripper, drip line sources spacing and quantity and frequency of the irrigation (Lazarovitch et al., 2007; Nafchi et al., 2011; Elmaloglou et al., 2013; Hao et al., 2007). All of these factors lead to one of the major difficulties in using capacitance sensors, which is the high variability between sensors even if installed at equivalent positions in the soil (Intrigliolo and Castel, 2004). Nevertheless, once a sensor has been installed, the effects associated with its exact position, including the properties of the soil around it, will be nearly constant (Rolston et al., 1991). Hence, one approach to deal with the variability between sensors is to field calibrate each individual sensor after installation (Evett et al., 2008, 2009; Mittelbach et al., 2012; Singh et al., 2018). A simplified field calibration approach for practical use in irrigation is to rescale the measurements by each sensor as relative to the measurements recorded by the same sensor under conditions of soil water at field capacity. In addition, to simplify dealing with the daily pattern of soil water content, the interpretation can focus in the driest measurement recorded each day (Casadesús et al., 2012). The trend of this value, between consecutive days, has been proposed as an indicator of the resulting water balance in that period and has been used for tuning the water balance in an algorithm of automated irrigation scheduling (Casadesús et al., 2012).

The overall goal of this research was to demonstrate the feasibility of automated scheduling irrigation in orchards, where, in practice, size and structure of the canopy can be a common source of variation. In particular, this study focused at testing: (a) the suitability of water balance locally tuned by sensors as the basis for irrigation scheduling in drip-irrigated orchards, (b) the unmanned interpretation of soil moisture measured by capacitance sensors as a source of feedback for the scheduling algorithm, and (c) the performance of these combined approaches in the autonomous scheduling of irrigation in an apple orchard with heterogeneous vigour. The study was conducted with an experimental web application, IRRIX, which implements the proposed algorithms and the methods for unmanned interpretation of capacitance sensors. On an apple orchard with heterogeneous vigour, sectors with larger and smaller trees were scheduled during two seasons by the automated system using capacitance sensors. The trial looked at how the automated system behaved on sectors with different tree vigour and whether, with identical configuration, it was able to provide differential irrigation according to the differences in tree vigour. Additionally, the automated system was compared with manual scheduling by a classical water balance and with the actual evapotranspiration determined by a weighing lysimeter located in the same orchard.

2. Materials and methods

2.1. Experimental design and irrigation treatments

The apple orchard (*Malus domestica* Borkh. cv 'Golden Reinders') was located at the IRTA-Lleida Experimental Station in Mollerussa (41.6 °N, 0.8 °E, 260 m above sea level), Lleida, Spain, with a dry continental mediterranean climate. Apple trees had been planted in 2011, spaced at 3.63 m x 1.2 m oriented north-south. Irrigation was provided by means of a single pipe with drippers every 0.6 m, whose delivery rate was 3.5 $dm^3 h^{-1}$. Some properties of the soil are shown in Table 1. One fraction of this plantation had been replanted after a previous apple plantation and, in this area, the trees were homogeneously smaller than in the rest of the orchard because of the apple tree replant disease (Laurent et al., 2010; Singh et al., 2017). The average Trunk Cross Sectional Area (TCSA) in the unaffected area was 40.55 cm^2 while in the affected area it was 27.94 cm^2. The trial consisted of the automated scheduling of two independent irrigation sectors, one in the area of larger trees (AUTO-L) and the other in an area with smaller trees (AUTO-S). These were compared with two sectors scheduled manually following a classical water balance, one with larger trees (MANUAL-L) and the other with smaller trees (MANUAL-S).

Manual irrigation scheduling consisted of the application of the FAO's water balance (Allen et al., 1998), on a weekly basis, by an experienced irrigator, using ET_O from the previous week recorded by a weather station located in the same farm and crop coefficients (K_C) determined in previous years by the weighing lysimeter included in the same orchard. In these sectors, irrigation was controlled by solenoid valves operated by a commercial automata, Agronic 4000 (Sistemes Electrònics Progrés, Palau d'Anglesola, Lleida, Spain) which was programmed remotely, every Monday, through the desktop application provided by the manufacturer. All irrigation sectors were equipped with the same model of water meter, CZ3000 (Contazara, Zaragoza, Spain), that were recorded at least twice per week, apart from the scheduling application. The manual scheduling made no distinction between MANUAL-L and MANUAL-S and applied a homogeneous irrigation program to the whole orchard, based on the estimated requirements of the larger trees, which mirrors the expected practice in a commercial farm.

2.2. Deployment and management of the automated scheduling

One datalogger, model CR800 (Campbell Scientific, INC., Logan,

Table 1
Soil properties sampled in the experimental site at two depths.

Depth (m)	0 - 0.2	0.2 - 0.4
Silt ($0.002 < d < 0.05$ mm) %	40.70	40.60
Clay ($d < 0.002$ mm) %	23.50	23.90
Sand ($0.05 < d < 2$ mm) %	35.80	35.50
USDA Soil Classification	Loamy	Loamy
Soil Water content at field capacity (33 K Pa) $m^3 m^{-3}$	0.38	0.37
Soil water content at wilting point (-1500 KPa) $m^3 m^{-3}$	0.17	0.17
Apparent density (Kg m^{-3})	1480	1500

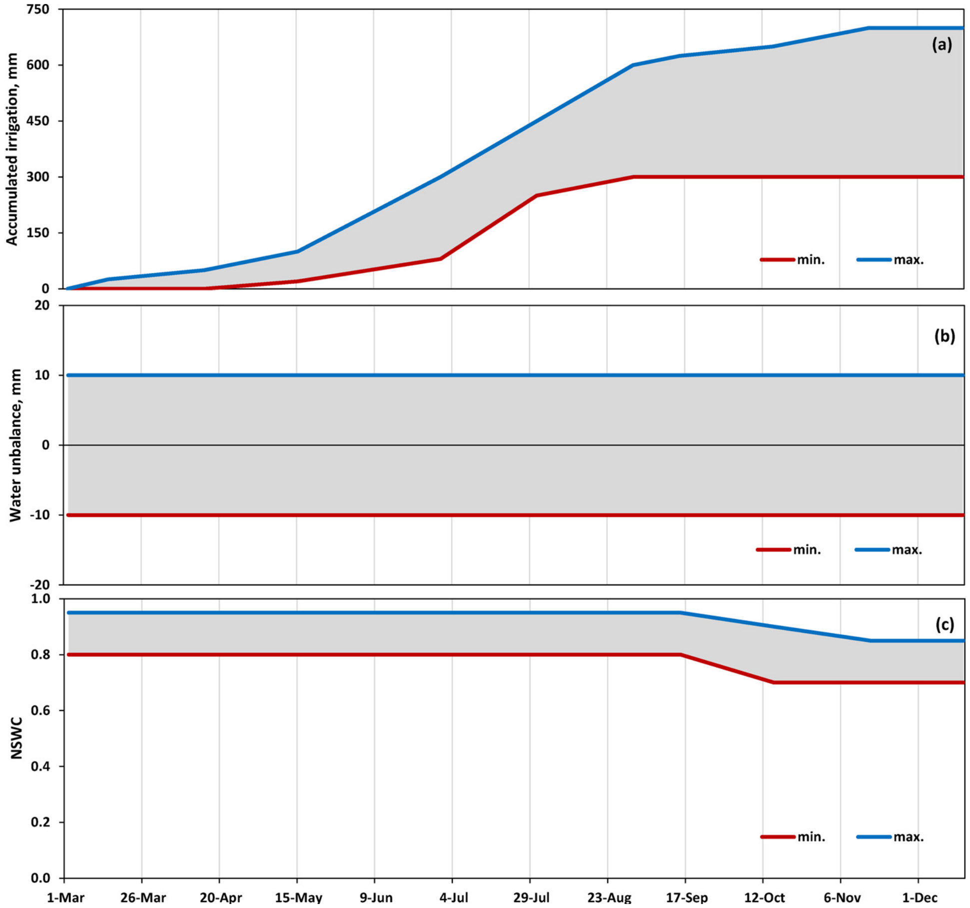

Fig. 1. Seasonal plan configured in IRRIX for AUTO-L and AUTO-S. The plan specifies (a) acceptable range of irrigation, (b) acceptable weekly water unbalance and (c) crop's water comfort in terms of the Normalized Soil Water Content (NSWC) recorded by sensors.

UT, USA) was used in the automated sectors for both recording sensors and commanding irrigation valves. The datalogger was equipped with a multiplexer AM16/32 (Campbell Scientific, INC., Logan, UT, USA), to increase the number of sensor channels, which were measured every 15 s and the average of 5 min was stored. A 3 G modem MTX-3 G-JAVA (MTX, Flexitron Group, Madrid, Spain), allowed remote communication through Internet Protocol. In addition, a four-channel latching relay LR4 (Campbell Scientific, INC., Logan, UT, USA) enabled the datalogger open and close the irrigation valves of the AUTO sectors, model ¾" AquaNet Plus (Netafim). The program in the datalogger, written in CR Basic (Campbell Scientific, INC., Logan, UT, USA), implemented the functionalities of an irrigation automata. Four times per day, the web application polled the datalogger for new sensor data and once per day, typically at 02:30 GMT, IRRIX sent to the datalogger the irrigation doses of each sector, in mm, for the new day. Communication between the IRRIX server and the datalogger used the API PackBus SDK (Campbell Scientific, INC., Logan, UT, USA). During the day, independently for each sector, at the appointed time, 8:00 AM, the datalogger started irrigation and ended it when it had measured the scheduled dose.

Each automated sector was equipped with six capacitance-type soil moisture sensors, 10HS (METER Group, Pullman, WA, USA), which were recorded by the datalogger in units of soil water content ($m^3 m^{-3}$) using the general calibration for mineral soils proposed by the manufacturer. These sensors have one body with two 14.5 cm long prong, spaced 3.3 cm, which gives an apparent permittivity measurement volume of around 1 dm^3 (Sakaki et al., 2008). All soil sensors were installed at 30 cm depth, three of them centered 15 cm from the vertical of the dripper, perpendicular to the irrigation pipe, and the other three at the mid-point between two drippers. Each automated sector was equipped with a water meter with a resolution of one pulse per litter, model Multijet M15 (Arad Group, Dalia, Israel), which were used by the datalogger for controlling the delivery of the appointed doses. In addition, a temperature sensor, model VP3 (METER Group, Pullman, WA, USA), provided a continuous measurement of air temperature that was used by IRRIX for the estimation of ET_O using Hargreaves equation (Hargreaves and Samani, 1985).

The settings of AUTO-L and AUTO-S in the automated scheduling application were exactly the same, while they were equipped with separate sets of soil moisture sensors which would provide independent feedback to the scheduling algorithm.

2.3. *Web platform for irrigation control: IRRIX*

IRRIX is a custom-made software for research on sensor-based irrigation scheduling. It can operate autonomously during the whole irrigation season, with a daily routine that includes uploading sensor data from the field, analysing those data, updating the water balance, deciding the next irrigation doses at each plot and transmitting them to the automata in the field. The scheduling approach used by IRRIX consists of estimating the crop water requirements by the method of water balance (Allen et al., 1998) and use the feedback from sensors for adjusting empirically the irrigation doses of each sector (Casadesús et al., 2012). Basically, the daily irrigation doses (DID), in mm, were determined on a daily basis as:

$$DID = ET_o \times K_x \tag{1}$$

Where ET_O was the reference evapotranspiration estimated by the Hargreaves equation using as input the air temperature recorded by the datalogger. K_X was initialized as a crop coefficient and, later on, independently for each sector, it was iteratively adjusted on a daily basis from feedback by the sensors.

In order to provide a seasonal vision of irrigation, and to enable in other studies the application of certain types of irrigation strategies, IRRIX requires the definition of a seasonal plan. The seasonal plans of IRRIX specify, for every day of the irrigation season, the acceptable ranges for (a) the accumulated irrigation; (b) the weekly water unbalance; and (c) the range of crop's water comfort in terms of the monitored Normalized Soil Water Content (NSWC). In the seasonal plan for this trial, the range of accumulated irrigation and the weekly balance were set sufficiently wide to avoid limiting the response to sensors (Fig. 1). Sectors AUTO-L and AUTO-S were configured exactly with the same seasonal plan, which was also the same for 2017 and 2018.

Interpretation of the soil moisture sensors by IRRIX focused at the trend, between consecutive days, of the driest measurement of each day, SWC_d. In order to manage the variability between sensors, IRRIX normalized those values between the measurable range of each individual sensor as defined by its actual reading at field capacity and the presumed wilting point for that soil textural class. Hence, the NSWC, dimensionless, was calculated as:

$$NSWC = \frac{(SWC_d - SWC_{WP})}{(SWC_{FC} - SWC_{WP})} \quad (2)$$

Where SWC_d was the driest soil water content measured by the sensor at given day ($m^3\,m^{-3}$), SWC_{FC} was the highest daily minimum of the soil water content (SWC_d) recorded by a sensor in a period of reference at the start of the season, under conditions near field capacity. In this context, the purpose of SWC_{FC} is just to provide an empirical reference for that sensor near its high end of scale. Fig. 2 shows an example of the empirical setting of SWC_{FC} for one sensor. Since normal growing conditions were far from wilting point, SWC_{WP} was not empirically based but set at the typical SWC at wilting point for that soil textural class. Table 2 shows the references set to the different sensors involved in this study.

In order to enforce its tolerance to sensor failures, the daily analysis of sensor data by IRRIX included rating the reliability of each sensor. These automated ratings started assigning to each sensor a reliability of 1.0 and when IRRIX detected values out of range, noise or abnormal patterns, the reliability of the sensor was penalized, which could decrease its value down to 0.0. The advantage of this method is that, if a sensor is broken or disconnected for any reason, IRRIX can automatically detect this situation, assign it a reliability of 0.0 and keep the aggregated value safe from its influence. To obtain a single value to summarize the state of an irrigation sector, IRRIX aggregated the NSWC obtained by the six sensors installed on a sector through a weighted average. In this trial, the weight of each sensor was its current rating of reliability, updated with the same set of data being summarized.

In order to provide feedback to the scheduling algorithm, IRRIX evaluates every day the state of an irrigation sector as either "to dry", "to wet" or "fitted". From the current value of aggregated NSWC and its trend in the last 3 days, it calculates the projected value after 3 days, $NSWC_{+3d}$. If $NSWC_{+3d}$ is below the comfort zone specified in the seasonal plan, then the state of that sector is evaluated as "too dry" and the response of IRRIX consists of increasing K_X by the estimated amount to fill in three days the soil wet bulbs up to the water content corresponding to the midst of the comfort zone. If $NSWC_{+3d}$ is above the comfort zone, it is evaluated as "too wet" and the response aims at reaching the midst of the comfort zone at the wet bulbs in 7 days. In either case, the change in K_X is conditioned to fulfil the conditions of accumulated irrigation and water unbalance specified in the seasonal plan.

Table 2
References used by IRRIX for normalizing the daily driest measurements to the span between SWC_{WP} and SWC_{FC} for each sensor. The values of SWC_{FC} were assigned empirically in March 2017 as shown in Fig. 3. The values for SWC_{WP} were set to the presumed soil water content at wilting point for this soil texture.

sensor	AUTO-L		AUTO-S	
	SWC_{WP}	SWC_{FC}	SWC_{WP}	SWC_{FC}
1A	0.15	0.363	0.15	0.356
1B	0.15	0.364	0.15	0.347
2A	0.15	0.368	0.15	0.318
2B	0.15	0.360	0.15	0.338
3A	0.15	0.392	0.15	0.324
3B	0.15	0.384	0.15	0.345

2.4. Measurement of ET_C by weighing lysimeter

The same orchard where this trial was conducted is equipped with two weighing lysimeters that provide a continuous measurement of crop evapotranspiration (Girona et al., 2004). These lysimeters contain four apple trees each, grown in equivalent conditions than the rest of the plantation. The ET_O used in the lysimeter was the Penman-Monteith evapotranspiration, determined by an automated meteorological station, located next to the orchard, operated by the Catalan Meteorological Service. Due to maintenance operations, in the period from March to July 2017 the lysimeters were not operative and the daily ET values for that period were estimated from the K_C values determined in 2018 corrected by the ratio between K_C measured in August of both years, as:

$$ET_{d2017} = ETo_{d2017} \times Kc_{d2018} \times \frac{Kc_{August2017}}{Kc_{August2018}} \quad (3)$$

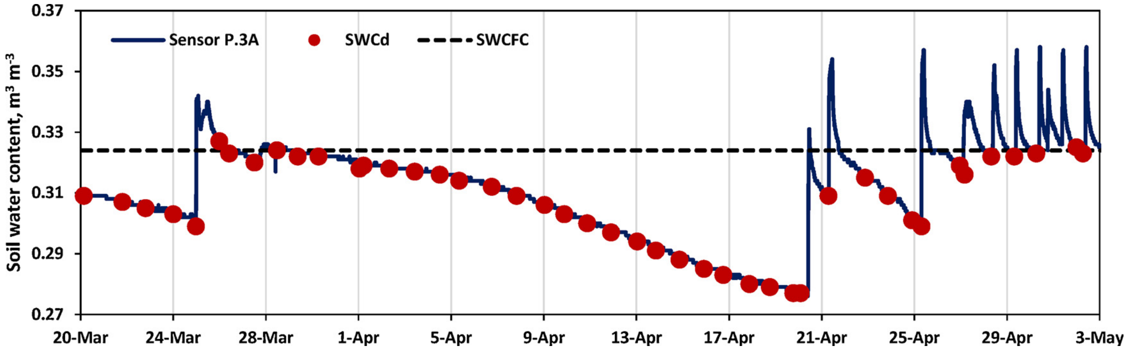

Fig. 2. Example of setting the reference of a sensor at field capacity, SWC_{FC}. Following rainfall (33 mm) on March 24th, the daily driest measurement on March 28th was taken as the SWC_{FC} for this sensor. Irrigation started in April 20th. The continuous line is the data recorded by the sensor. Dots are the driest measurement each day, SWC_d.

2.5. Physiological and agronomical measurements

Stem water potential (SWP) was determined once a week using a pressure chamber (3005-series portable plant water status console, Soil Moisture Equipment Corp., Model 3005, Santa Barbara, CA, USA) following the method described by McCutchan and Shackel (1992) procedure. Measurements were made at solar noon on shaded leaves located close to the main trunk. Previously, leaves were covered with plastic sheathes with aluminium foil bags to minimize transpiration and keep in balance with the xylem of the tree.

The differences in vigour between the large and small trees were quantified in terms of fraction of photosynthetically active radiation intercepted by the canopies (FIPAR) along the whole day. The measurement method was similar to the Fisheye Photography described by Wünsche et al. (1995) and consisted on taking hemispheric photos from below the tree, following a pattern that covered the entire planting space. The photographs were taken with a digital camera Nikon D70 and a 10–17 mm AT-X Tokina fish-eye lens on a self-leveling support that held the camera 10 cm above ground. The photographs were processed to calculate the daily solar path on each picture and analyse the fraction between treetop pixels and background -i.e. blue sky- at the different sun positions along the day.

To determine yield and its components, the central five apple trees of each plot were individually harvested and the collected fruits counted and weighted to determine total yield (kg of fruits per tree) (Yield) and after passing the fruits for a grade, and removing fruits smaller than 70 mm, the remaining ones were used to determine Commercial Yield ($kg{\cdot}tree^{-1}$ and $t{\cdot}ha^{-1}$) (CY). Yield Index (YI) (kg of total $yield{\cdot}CTSA^{-1}$) ($kg{\cdot}cm^{-2}$) and Commercial Yield Index (CYI) (kg of commercial $yield{\cdot}CTSA^{-1}$) ($kg{\cdot}cm^{-2}$) were also determined to compare the effects of treatments in fruit production. Because of the location and distribution of the different plots within the orchard, each individual tree was used as a repetition resulting a strip plot design. Statistical analyses were carried out with SAS (SAS Institute, Cary, NC, USA, version 9.4).The effects of treatments were analysed by means of the general linear model (GLM) procedure, and differences among means were compared with the LSmeans followed by Tukey-Kramer adjustment, with the statistical significance established at $P \leq 0.05$.

3. Results and discussion

3.1. IRRIX performance and interpretation of sensor data

The trees in sectors AUTO-S and MANUAL-S had, through the duration of the trial, a visually lower vigour than those in the rest of the plot, including AUTO-L, MANUAL-L and the lysimeter. The ratio between $FIPAR_{AUTO\text{-}S}$ and $FIPAR_{AUTO\text{-}L}$ was persistently around 0.88 during the whole period of study (Fig. 3).

Interaction of the research team with the web application IRRIX concentrated in 2017 before season, when the seasonal plan was established and the references for each sensor were set. During the irrigation seasons of 2017 and 2018 IRRIX operated autonomously and the participation of the research team consisted in supervising the normal development of the irrigation plan, by connecting once/twice per week to IRRIX and checking for common anomalies that would require a physical repair, such as malfunction of the irrigation system or the sensors.

Data recorded by soil moisture sensors used to show clear responses to irrigation, rain and water uptake by the crop, as illustrated in Fig. 4, which shows a period that includes rain events and an interruption in water supply. As shown in Fig. 4a, at the daily scale the timing of irrigation was programmed to concur with ET_O. However, irrigation did not necessarily fluctuate between days with ET_O, because the control algorithm may vary at any time the proportionality between irrigation and ET_O. The soil water content recorded by sensors showed a clear daily pattern, with a peak during irrigation, followed by a decrease that may be attributed to the redistribution of water in soil plus uptake by roots. In days without irrigation, sensors showed a clear decrease in water content during transpiration hours and still values at night. Most rain events could be observed as a rise in soil water content unaligned with irrigation.

Despite the coherent responses of individual sensors to irrigation, rain and water uptake by the crop, a large variation was observed between sensors, which fluctuated with similar patterns but shifted at different positions in the scale of soil water content (SWC). As shown in Fig. 4b, the scatter between sensors in SWC was twice as large as the typical fluctuation of a sensor in a daily cycle and, also, larger than the effect of suppressing irrigation for several days. Sensor-to-sensor variability in the soil moisture recorded by capacitance-type sensors has frequently been reported (Intrigliolo and Castel, 2004; Hignett and Evett, 2008; Kizito et al., 2008; Kargas and Soulis, 2011). Such variation could partially be explained by the small volume of soil perceived by a capacitance sensor, around 1 dm^3 in sensor 10HS (Sakaki et al., 2008), whereas the soil electrical permittivity at that scale of observation may vary at different spots as affected by macropores, soil density or stones (Hignett and Evett, 2008). In addition, under conditions of localized irrigation wet bulbs develop below the emitters, determining a very heterogeneous pattern of soil moisture (Samadianfard et al., 2012). To cope with such variability, some authors recommend installing sensors at two or more depths or positions (Dursun and Ozden, 2011; Casadesús et al., 2012; Lea-Cox et al., 2013; Soulis et al., 2015; Domínguez-Niño et al., 2019).

Regarding the interpretation of sensor data, an approach for handling the variability between sensors is to look at the dynamics rather than the absolute readings. IRRIX focuses on the trend of SWC_d (Fig. 4b), with the assumption that the driest situation after a cycle of irrigation, redistribution and uptake by roots summarizes the aggregate outcome of those processes. Moreover, the trends of SWC_d in consecutive days may follow the soil water balance and be used for rating the fit between irrigation and the crop water requirements (Casadesús

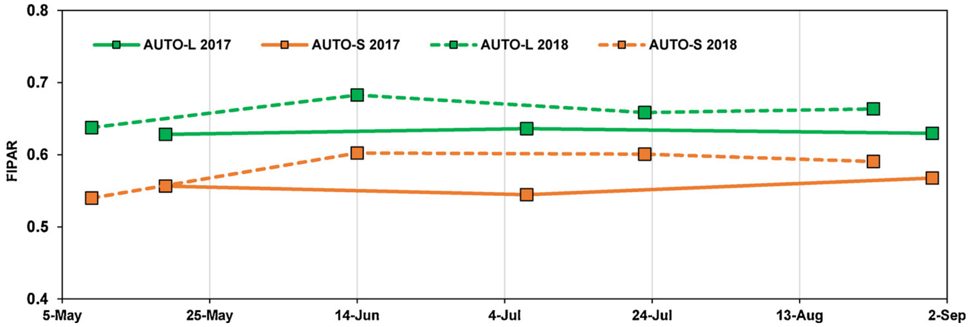

Fig. 3. Fraction of intercepted photosynthetically active radiation (FIPAR) in the irrigation sectors with large (AUTO-L) and smaller (AUTO-S) trees during the years 2017 and 2018.

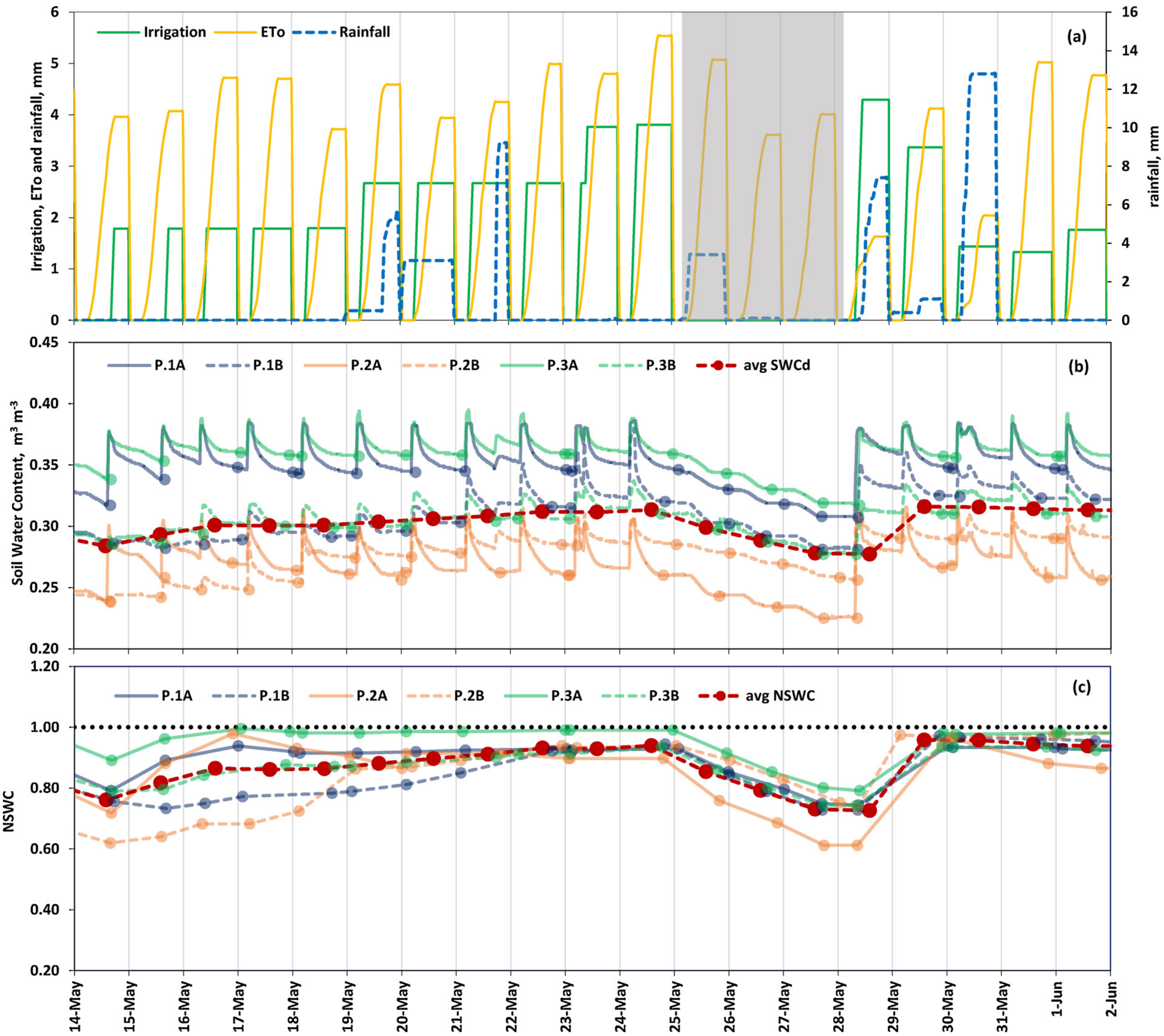

Fig. 4. Example of sensor data for the sector AUTO-S in an early part of the season of 2018. (a): irrigation, ET_O and rainfall, and how they accumulate each day. Notice an interruption of irrigation for three days due to an external anomaly, marked in grey. (b): the original soil water content, SWC, recorded by the six soil moisture sensors installed in AUTO-S. On each line, a dot indicates the daily driest measurement, SWC_d. (c): the SWC_d of each sensor normalized to the span between its readings at wilting point and field capacity, NSWC.

et al., 2012). Besides its dynamics, another informative trait of SWC_d is its relative position within the particular span of measurements by that sensor, which can be specified by normalizing the value of SWC_d between the readings of that sensor at wilting point and field capacity (Fig. 4c). Hence, one normalized, the dataset including different sensors can offer a more straightforward view of the soil water dynamics than the original readings, whose overall pattern may be partly obscured by the variability in the baseline of each sensor. Additionally, as it can be observed in this example, variability between sensors was highest when the average soil moisture was lowest, and that the variability was reduced at higher soil moisture, specially following rain. This observation may endorse the interpretation that, under localized irrigation, short irrigation doses can cause larger variability because while some spots can still be wetted, the shrunk wet bulbs leave some spots outside the wetted volume. Swelled bulbs may re-include those spots and the sensors there and, hence, reduce their variability. Accordingly, aggregation of the different sensors once normalized may offer a sounder basis for decision making compared with the direct readings.

3.2. Applied irrigation

Overall, the seasonal amount of irrigation applied in AUTO-L was similar to that applied by an expert using water balance in the MANUAL treatment, and similar also to the ET_C measured by the lysimeter, while AUTO-S applied 24% less irrigation (Fig. 5). In 2017, AUTO-L applied a total irrigation volume of 666.0 mm, similar to MANUAL (only differed by a 1.0%), while in 2018, AUTO-L irrigated 724.7 mm, 4.9% more than MANUAL. In both years, AUTO-S applied lower doses than AUTO-L (23.7% and 27.2% less in 2017 and 2018, respectively) and MANUAL (24.5% and 23.4% less in the year 2017 and 2018, respectively). The seasonal amount of irrigation applied in AUTO-L was in agreement with the ET_C measured by the lysimeter (differences of 6.1% and 0.9% in the years 2017 and 2018 respectively), while the irrigation in AUTO-S was considerably lower than the ET_C at the lysimeter (-18.7% and -27.9% for the year 2017 and 2018 respectively). Fig. 5 shows how those volumes accumulated along the season.

3.3. Response of the automated irrigation scheduling

With a greater detail, the functioning of the automated scheduling is

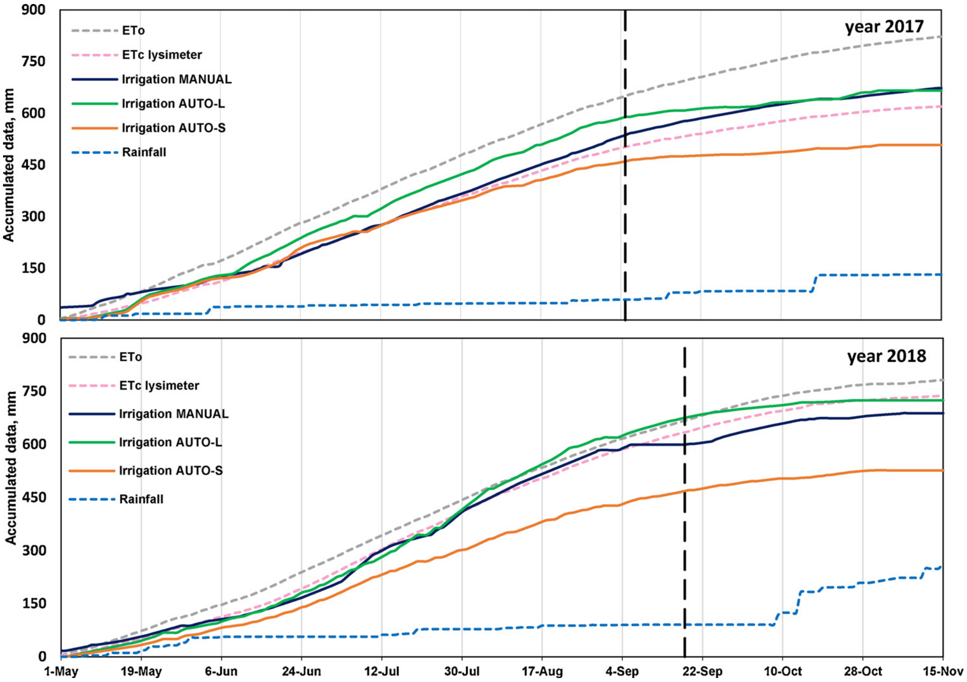

Fig. 5. Seasonal accumulated values of ET_O, ET_C, irrigation and rainfall in 2017 and 2018. Vertical dashed line indicates harvest day.

illustrated in Fig. 6. The span of time shown in the figure corresponds to the part of the season in 2018 where the irrigation requirements were highest. In that period, the measured ET_O fluctuated between 3.4 and 6.1 mm and ET measured by the lysimeter was slightly higher than ET_O, with an average K_C of 1.03. In both AUTO-L and AUTO-S, IRRIX tried to keep the soil moisture, here expressed as NSWC, within the comfort zone specified in the seasonal plan. However, the observed pattern of soil moisture response to irrigation by these two sectors was different, which caused that they required different adjustments to maintain the comfort zone. AUTO-L used to remain in the lower part of the comfort zone and several times it decreased below the lower limit of comfort. Hence, IRRIX often evaluated that the state of the soil, or its projection for the next days, was “too dry” and it adjusted the irrigation coefficient of AUTO-L upwards. On the other hand, AUTO-S used to remain easily in the upper part of the comfort zone and several times its moisture level surpassed the upper limit of comfort. Consequently, in those occasions where IRRIX evaluated that the state of the soil, or its projection in the next days, were “too wet”, IRRIX adjusted the irrigation coefficient downwards. As a result, within that period, the average irrigation coefficient for AUTO-L was 0.97, and 47.2% of the time it was above the presumed K_C value. Meanwhile, the irrigation coefficient for AUTO-S was on average 0.75, and most of the time below 1.0, which was the presumed K_C at the time of preparing the seasonal plan. All those adjustments of the irrigation coefficients produced different irrigation doses in the two automated sectors, with average daily doses of 5.6 mm and 4.4 mm in AUTO-L and AUTO-S, respectively, and 73.6% of the time AUTO-S with a lower irrigation dose than AUTO-L.

Incidentally, within the period shown in Fig. 6, a power cut following a small storm in July 20th produced an interruption of irrigation for two days, which triggered different responses in the two automated sectors. In AUTO-L, the lack of irrigation immediately produced a decrease in soil moisture, which stimulated the irrigation coefficient and helped in approaching the comfort zone after the incident. In contrast, in AUTO-S, the soil moisture was maintained probably because the rainfall could compensate the missing irrigation and, furthermore, the next irrigation after this event raised the soil moisture above the comfort zone, causing a decrease in the irrigation coefficient some days later.

These results show how the control algorithm of IRRIX, without using information of tree vigour, applied a differential irrigation because the moisture sensors perceived that soil water was depleted faster in AUTO-L than in AUTO-S. Previous studies at the same site had looked at the effect of tree canopy on irrigation requirements. In particular, lysimeter data from a previous apple plantation showed a strong relationship between FIPAR and K_C (Girona et al., 2011). Using the relationship described in Girona et al. (2011) with the FIPAR measured in this trial, we estimate that K_C at AUTO-S would be 21% below the K_C at AUTO-L. This value fits closely with the response of the automated algorithm in the present study, where the amount of irrigation applied to AUTO-S was 23% lower than the amount applied to AUTO-L.

3.4. Physiological and agronomical results

Measurements of stem water potential were aligned with the values obtained by Girona et al., 2010 (between -0.8 MPa and-1.3 MPa). The measured stem water potential showed slightly more negative values in the smaller trees, regardless of whether irrigation was scheduled automatically or manually (Fig. 7). More precisely, during the year 2017, in MANUAL-L and AUTO-L, the stem water potential remained between -1.3 MPa and-0.7 MPa and in MANUAL-S and AUTO-S they were between -1.5 MPa and-0.7 MPa. During the year 2018, in MANUAL-L and AUTO-L, the stem water potential remained between -1.2 MPa and-0.7 MPa and in MANUAL-S and AUTO-S they were between -1.3 MPa and-0.7 MPa. In the manual treatment, it can be noticed that, even though MANUAL-S received the same irrigation than MANUAL-L, their stem water potential used to be lower. This may be explained by the diagnosed cause of their smaller size, the apple replant disease. That disease affects the root system (Laurent et al., 2010; Singh et al., 2017) and the lower SWP may be a consequence of the limited hydraulic conductance of their root system. Therefore, taking into account the measured SWP and the effect of this disease, the data suggests that trees in AUTO-S were not water-limited by irrigation.

The yield of this apple orchard (Table 3) showed a large variation between the two years of the study, mainly attributed to a poor fruit set in 2017, which was also clearly identified in the whole area. However, no statistical differences were found between treatments for the main productivity indicators when analysing the harvest data for the whole experimental period (Table 3). Because of the commercial thinning

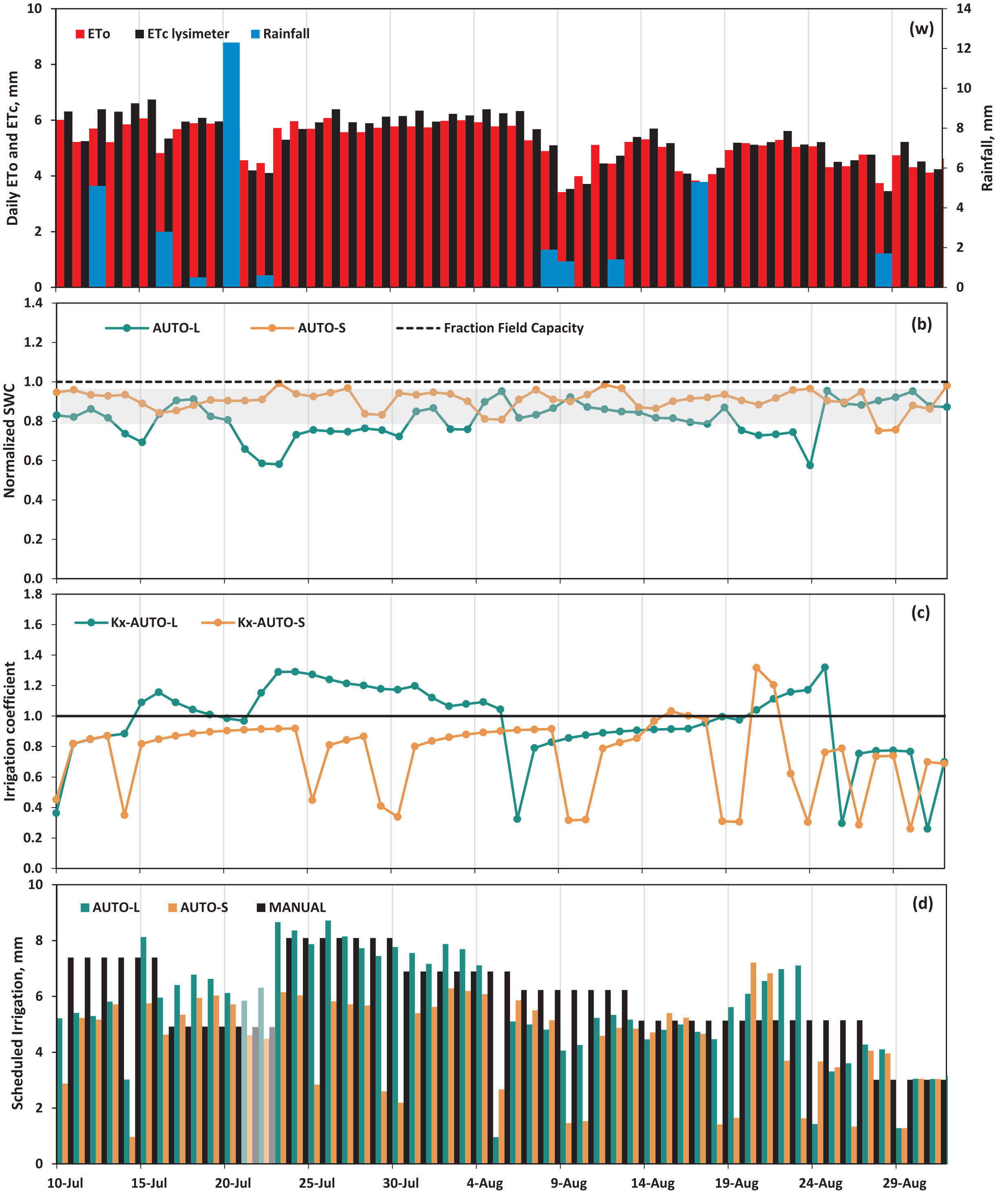

Fig. 6. Example of the adaptive response of the automated irrigation scheduling during the period of highest irrigation demand in 2018. (a): ET_O, rainfall and ET_C by a weighing lysimeter with large trees. (b): soil moisture in the two automated sectors (AUTO-L and AUTO-S), normalized to sensor-specific references, with a grey band indicating the comfort zone configured in IRRIX. (c): response of IRRIX, modulating the irrigation coefficient K_X in the automated sectors. (d): irrigation doses scheduled on each automated sector and by a manual water balance. In 21st and 22nd July the schedules were not applied because of a power cut in the farm. Labels L and S indicate large and small trees, respectively.

practices, no differences were observed on yield between large and small tress, and more important no statistical significant differences were found on CYI (commercial yield index) and YI (yield index). Therefore, it can be stated that no negative effects of the automated management were observed on yield, either in the larger trees, which were irrigated a similar amount to classical water balance, or in smaller trees, where the automated algorithm saved 23% of irrigation volume.

3.5. Irrigation scheduling approach

Overall, this study tested the performance of scheduling irrigation through an automated water balance approach tuned by capacitance-type soil moisture sensors. Here, we observed how the adaptive response allowed spontaneous adjustment to a component of the water balance, in this case the low ET associated to low vigour, that had not

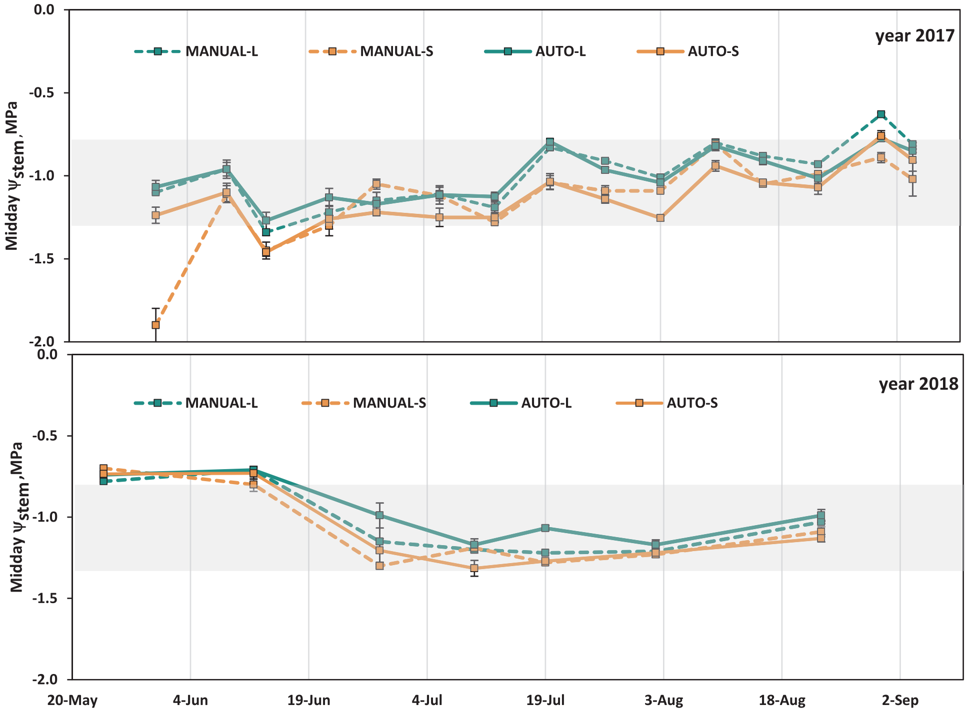

Fig. 7. Stem water potential on the different irrigation sectors in 2017 and 2018. AUTO sectors were automated with IRRIX. MANUAL sectors were scheduled by classical water balance. Labels L and S indicate large and small trees, respectively. Error bars indicate the standard deviation. Grey band indicate the acceptable range of stem water potential in non-water limited conditions.

Table 3

Analysis of Variance and Mean Separation summary for the orchard yield parameters whole experiment (two years).

		Variables					
	df	CY	FL	FFW	YI	CYI	TCSA
		Signification (Pr > F)					
Model	12	0.0386	0.0461	0.1388	0.0343	0.0856	0.0059
Treatments	3	0.5544	0.0876	0.0077	0.6764	0.1537	0.0001
REP	4	0.9400	0.9855	0.9446	0.5946	0.4044	0.2255
Year	1	0.0001	0.0003	0.3956	0.0001	0.0018	–
Rep * Year	4	0.9034	0.9029	0.4846	0.9889	0.9554	–
		TRT Mean Separation					
MANUAL-L		41826	163	176.6 b	0.648	0.445	40.93 a
AUTO-L		39771	105	213.3 a	0.560	0.435	40.17 a
MANUAL-S		37496	112	177.4 a	0.692	0.588	28.50 b
AUTO-S		34089	96	173.9 b	0.709	0.628	27.38 b
		Year Mean Separation					
2017		28815 b	79 b	181.6	0.431 b	0.401 b	–
2018		47763 a	160 a	188.9	0.873 a	0.648 a	–

CY = Commercial yield (kg·ha^{-1}); **FL** = Fruit Load (fruits·tree^{-1}); **FFW** = Fruit Fresh Weight; **YI** = Yield Index (Total production·CTSA^{-1})(kg·cm^{-2}); **CYI** = Commercial Yield Index (YI·CTSA^{-1}) (kg·cm^{-2}); **TCSA** = Trunk Cross Sectional Area (cm^2); **df** = degrees of freedom; Means within column (within treatments or years) followed by different letters were significantly different at P ≤ 0.05 using Tukey-Kramer adjustment.

been considered in the original configuration of the water balance. This experience may exemplify the capacity of this approach to confront site-specific conditions that would be difficult to parameterize in a deterministic model. As another example, a previous version of the algorithm showed a spontaneous adaptation to the presence of groundwater (Casadesús et al., 2014), which would otherwise be omitted in the management of irrigation.

Regarding the choice for a base scheduling method, the water balance approach provides an effective method for fitting irrigation to the encountered weather conditions (Allen et al., 1998). While irrigation controllers based on water balance are commercially available for turfgrass (Davis and Dukes, 2014), their application to orchards would be more complicated because of the much larger uncertainty of crop coefficients. That uncertainty was solved here through feedback from sensors, which provided an empirical site-specific adjustment of the ratio of irrigation to ET_O. Other alternative sensor-based approaches use predefined thresholds either to trigger irrigation when the soil is too dry (Dukes and Scholberg, 2005; Osroosh et al., 2016; Vera et al., 2019) and/or to bypass a timer-triggered irrigation when the soil is too wet (Smajstrla and Locascio, 1996; Cáceres et al., 2007; Muñoz-Carpena et al., 2008). Some advantages of water balance tuned by sensors are that its response is smoother and more predictable than occasional switching on/off valves. Additionally, it allows modulating the daily irrigation depth of each sector without disturbing the hydraulic scheme for the whole farm, while irrigation triggered directly by sensors can switch valves on at arbitrary times, complicating the operation of the farm's hydraulic system.

4. Conclusions

The results of this trial show the feasibility of automated sensor-based scheduling of irrigation in orchards. The algorithm, based on the approach of water balance and tuned locally through feedback from sensors, provided precise irrigation doses along the season, adapting itself to weather conditions and to the seasonal vegetation cycle of the crop.

Capacitance sensors have successfully been used to provide automated feedback to the scheduling algorithm. In spite of the observed sensor-to-sensor variability – comparable with that reported by other authors – the approach followed here allows a consistent mechanism for their unmanned interpretation and integration with decision-making. First, the summarization of the daily fluctuation of soil water content on the daily driest measurement focuses the analysis on a simple parameter whose day-to-day dynamics retains much of the information on the fit between irrigation and the crop water demand. Second, the sensor-specific normalization of those daily values reduces the scatter between sensors and brings a more intelligible dataset on which to base automate control. This trial shows how the irrigation doses determined by the algorithm are aligned with the ET measured on the same orchard by a weighing lysimeter. The irrigation doses applied by the automated approach are also comparable with those by a skilled irrigation technician though requiring less labour effort. Furthermore, the tested algorithm adapts itself to heterogeneous tree vigour, applying less irrigation to sectors with smaller trees in a proportion that fits previous lysimeter studies on the relationship between K_C and FIPAR. Therefore, this indicates that the algorithm could be suitable for horticultural application, where adaptation to site-specific vigour are a common concern.

Declaration of Competing Interest

None.

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