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Processing Soil Water Content Measurements to Estimate Crop Water Requirements and Optimize Irrigation Supply

F. Karam[*], **A. Mouneimne**[*], **F. Aichouche**[**,***], **A. Rapaport**[****], **J. Harmand**[**]

[*]*Faculty of Agriculture, Lebanese University, Dekwaneh, Meten, Lebanon (e-mail: fadkaram@gmail.com, abdul.mouneimne@gmail.com)*
[**]*LBE, Univ. Montpellier, INRA, Narbonne, France (e-mail: jerome.harmand@inra.fr)*
[***]*Abou Bekr Belkaid University, Tlemcen, Algeria (e-mail: aichouche.farouk@gmail.com))*
[****]*UMR MISTEA, Univ. Montpellier, INRA, Montpellier, France (e-mail: alain.rapaport@inra.fr)*

Abstract: In this paper, we present a new procedure using an observer for estimating soil water content (SWC), a key parameter of soils when dealing with the adaptation of water plant requirements within the framework of irrigation. Results showed that the estimation of *SWC* by means of the observer was good. On the one hand, the estimation of the unknown part of the soil-plant water balance equation (negative component) has been found to be noise-free and values of evapotranspiration *ET*, drainage D_r and runoff R_o were estimated after filtering the simulated data. On the other hand, *SWC* has been found to increase after each water supply and decrease in the interval separating two successive irrigations. In addition, crop water requirements of avocado were found to be as much as 622 mm (for the 2016 dataset) and 380 mm (for the 2018 dataset) during the growing season from June throughout September. The findings of this research helped accounting for the net water requirements of avocado with the aim to optimize irrigation supply and provide guidelines to growers and farmers on sustainable irrigation of this crop under Lebanon's Mediterranean climate and limited water resources.

Keywords: Irrigation, optimization, soil water content, resistive sensor.

1. INTRODUCTION

Avocado (*Persea americana* Mill) is a subtropical tree native to Central America not very demanding in terms of light and water and can withstand reduced water supplies (Nakasone and Paull, 1998; Boyer, 1985; Boyer and Cutting, 1986; Boyer and Jackson, 2003). However, yields, fruit quality and tree health will suffer from unbalanced water management (Celedón *et al.,* 2012). When placed under water stress, avocado trees develop blockages, which are not reversible (Martens *et al*., 1994). Therefore, significant, sustained stress periods will result in lasting damage to avocado's tree capacity to draw water and nutrients (Dirou, 2003). With adequate water supplies, the trees will produce new shoots and fruits and the effect of the stress damage will diminish (Partridge, 1997; Carr, 2013).

The standard irrigation strategy for crops is to maintain a certain level of soil moisture in the top root zone within the Readily Available Water (*RAW*) range for water sensitive crops (-20 kPa maximum) throughout the growing period (Steduto et al., 2012; Müller et al., 2016). As avocado is an evergreen tree, the soil moisture should be monitored throughout the year and during the non-bearing period of the growth cycle. Irrigation is needed in summer and in some cases in spring whenever winter rainfall is not sufficient (Pegg *et al.,* 1986). In all cases, good irrigation management practices combined with good soil management result in increased productivity of avocado trees (Karam, 2014).

Under Mediterranean climate, characterized by hot and dry summers and dominantly humid winters, irrigation is practiced to restore water deficits due to high crop evapotranspiration (*ET*). In order to maintain adequate soil water content in the top soil profile, irrigation scheduling based on regular readings of the soil water content in the root zone has the advantage to supply the needed water requirements to crops to avoid prolonged periods of water stress. Avocado is known to have shallow root system expanding over the top 60 cm of the soil profile. Short irrigation intervals combined with reduced water applications have been shown to improve the tree performance and increase yield, while saving amounts of water that can be used to irrigate other crops (Karam, 2014).

A first objective of this study was to monitor at online basis soil water content (*SWC*) in the root zone by means of digital tensiometers and determine crop water requirements of avocado under Lebanon's Mediterranean climate. The second objective was to provide growers and farmers with practical information on sound irrigation management of this crop under the prevailing water shortages during summer period.

2. SOIL WATER CONTENT MEASUREMENT AND DYNAMICAL MODELING

2.1 Water Soil Content Measurement

Soil water potential (in cbar) in the 0–45 cm of the soil profile is currently measured with resistive devices. Such sensors respond to changes in soil water potential at the

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desired depth. This type of digital tensiometers is an electrical conductor and thereby provides relative indication of the soil moisture status. As the soil dries up, water is removed from the sensor and the resistance measurement increases. Conversely, when the soil is rewetted, the resistance lowers. This is a non-destructive method that provides accurate indication on the soil water availability to plants without any maintenance and can remain in the soil during long periods of time.

Using such sensors, values of soil water content (SWC, in cbar) can be measured online and converted into mm of water depth using the following simple conversion equation (Karam *et al*., 2014):

$$SWC(t)|_{mm} = \frac{\left(\frac{SWC(t)|_{cbar}}{100}\right) \times FC(\%v) \times 10}{15} \tag{1}$$

where 100 is a factor to convert from cbar to bar and 15 is the pressure (in bar) at permanent wilting point, while FC is field capacity (in % of volume). 10 is a conversion factor to convert water content volumetric water (in %) into mm of water depth (1 % of volumetric water corresponds to 1 cm or 10 mm of water depth).

2.2 Water mass-balance modelling

The water balance approach to irrigation scheduling keeps track of the soil water deficit by accounting for all water additions and subtractions from the soil root zone. Crop water consumption or evapotranspiration accounts for the biggest subtraction of water from the root zone while precipitation and irrigation provide the major additions (Andales *et al*., 2011). The different components of the soil–plant water balance can be used to write down the following water balance in soil over Q given period of time:

$$P + I - ET - D_r - R_0 \pm \Delta Q = 0 \tag{2}$$

where P is precipitation, I irrigation, ET evapotranspiration, D_r drainage, R_o runoff, and ΔQ the variation of soil water content during a given irrigation interval.

The mass balance (1) can be rewritten as the following continuous time ordinary differential equation:

$$dSWC(t)/dt = f(SWC(t))(P(t) + I(t) - ET(t) - D_r(t) - R_o(t)) \tag{3}$$

where SWC is the Soil Water Content while $f(SWC(t))=0$ if $SWC(t)<0$ and $f(SWC(t))=1$ otherwise to guarantee the positivity of SWC.

Remark: In this paper, we work with trees. Thus it is assumed that the volume of soil containing accessible water – the root zone - is constant. If we were considering developing crops, we would take into account its growing volume as proposed, for instance, in the model proposed in (Kalboussi *et al*., 2019).

The dynamic of SWC depends on two kinds of terms, that we will denote here as "inputs" because they act on its dynamic. Some of them are known (P and I notably) while others are unknown (as ET, D_r and R_o). Our objective is to estimate what contributes to the negative influence of SWC in order to compensate it with irrigation. In other terms, we aim at providing a systematic procedure to continuously estimate the sum $-ET$-D_r-R_o. To do so, we know the dynamic of the mass balance of water content in soil, *i.e.* (3), and the in-real-time (or online) measurement of $SWC(t)$ provided by (1).

Remark: In practice, SWC is measured at a given depth. In all rigor, we should write a model including the depth at which the sensor is positioned and write down the dynamic of SWC at this depth. However, this model would be much more complicated than (3). As a first approximation, we rather use (3) as a basis for estimating the unknown component of the dynamic of SWC as it is described in the next section. It is equivalent to assuming that water mass balance in soil is equivalent to a simple tank that fills up and empties depending on what is added (u) and withdrawn (w), respectively.

3. OBSERVER DESIGN FOR ESTIMATING CROP WATER REQUIREMENTS

In the following, we use systems theory to build an observer for the term $-ET$-D_r-R_o. From now on, we denote $u(t)=P(t)+I(t)$ and $w(t)=-ET(t)-D_r(t)-R_o(t)$. In a systemic approach, $u(t)$ is called a "known input" while $w(t)$ is qualified as an "unknown input". Equation (3) is then rewritten as:

$$dSWC(t)/dt = f(SWC(t))(u(t) + w(t)) \tag{4}$$

In a first attempt, it was assumed that $w(t)$ is an unknown constant (in practice it may vary slowly with time). Under this assumption, we can write the dynamic of w as:

$$\frac{dw}{dt} = 0 \tag{5}$$

Following the disturbance accommodation control theory (cf. for instance Harmand *et al*., 2000), we consider the "augmented" dynamical system under a matrix form:

$$\begin{bmatrix} \frac{dSWC(t)}{dt} \\ \frac{dw(t)}{dt} \end{bmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{bmatrix} SWC(t) \\ w(t) \end{bmatrix} + \begin{pmatrix} 1 \\ 0 \end{pmatrix} u(t) \tag{6}$$

which is simply a way of rewriting both (4) and (5) which are two simple first order differential ordinary equations in a concatenated manner as a single dynamical system of dimension 2.

In addition, recall that $SWC(t)$ is measured. Let us denote $y(t)=SWC(t)$. Referring to control systems theory, we can then build an "observer" (or an "estimator") for $w(t)$ – denoted $\hat{w}(t)$ – computed as the "output" of the following observer:

$$\begin{bmatrix} \frac{d\xi_1(t)}{dt} \\ \frac{d\xi_2(t)}{dt} \end{bmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{bmatrix} \xi_1(t) \\ \xi_2(t) \end{bmatrix} + \begin{pmatrix} 1 \\ 0 \end{pmatrix} u(t) + \begin{pmatrix} K_1 \\ K_2 \end{pmatrix} (y(t) - \hat{y}(t)) \tag{7}$$

which rewrites:

$$\begin{bmatrix} \frac{d\xi_1(t)}{dt} \\ \frac{d\xi_2(t)}{dt} \end{bmatrix} = \begin{pmatrix} -K_1 & 1 \\ -K_2 & 0 \end{pmatrix} \begin{bmatrix} \xi_1(t) \\ \xi_2(t) \end{bmatrix} + \begin{pmatrix} 1 \\ 0 \end{pmatrix} u(t) + \begin{pmatrix} K_1 \\ K_2 \end{pmatrix} y(t) \tag{8}$$

where $\hat{y}(t) = \xi_1(t)$ and $\hat{w}(t) = \xi_2(t)$ and $K^T=(K_1\ K_2)^T$ is the "gain" of the observer, chosen such that the system (8) guaranties that $\lim_{t\to+\infty}\left(y(t) - \hat{y}(t)\right) = 0$.

This modeling for $w(t)$ presents an important drawback: since it assumes w varies slowly with time (rigorously, it is a constant!), it will give bad results if it is not the case. In order to relax this hypothesis, we decided to "augment" the model chosen for w in assuming it is the output of a second order system. Such an hypothesis can be formalized in replacing the model (5) by the following differential system:

$$\begin{bmatrix} \frac{dw_1(t)}{dt} \\ \frac{dw_2(t)}{dt} \end{bmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{bmatrix} w_1(t) \\ w_2(t) \end{bmatrix} \tag{9}$$

with $w(t) = w_1(t)$.

In other terms, $w(t)=\alpha+\beta t$ is now the sum of an unknown constant α, and a line which the slope β, must be estimated.

In doing so, (6) is rewriten as:

$$\begin{bmatrix} \frac{dSWC(t)}{dt} \\ \frac{dw_1(t)}{dt} \\ \frac{dw_2(t)}{dt} \end{bmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \begin{bmatrix} SWC(t) \\ w_1(t) \\ w_2(t) \end{bmatrix} + \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} u(t) \tag{10}$$

Finally the observer equation can be deduced for the new unknown input model:

$$\begin{bmatrix} \frac{d\xi_1(t)}{dt} \\ \frac{d\xi_2(t)}{dt} \\ \frac{d\xi_3(t)}{dt} \end{bmatrix} = \begin{pmatrix} -K_1 & 1 & 0 \\ -K_2 & 0 & 1 \\ -K_3 & 0 & 0 \end{pmatrix} \begin{bmatrix} \xi_1(t) \\ \xi_2(t) \\ \xi_3(t) \end{bmatrix} + \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} u(t) + \begin{pmatrix} K_1 \\ K_2 \\ K_3 \end{pmatrix} y(t) \tag{11}$$

where $\hat{y}(t) = \xi_1(t)$ and $\hat{w}(t) = \xi_2(t)$ and $K^T=(K_1\ K_2\ K_3)$.

While system (4) is a system with one known and one unknown input, system (8) - or (11) - is a system – of higher dimension – but with two known inputs ($u(t)$ and $y(t)$). In other words, replacing a system of one dimension with an unknown input with a higher dimensional system with only known inputs allows us to estimate the unknown input of the latter. In addition, playing with K, we can choose the "speed" (or the "rate") at which the estimate converges towards the 'true' value (the actual value) of the unknown input. Of course, to guarantee that property, the system must be observable what can be easily checked for the above system whatever the model chosen for w.

In practice, the observer (11) can then be used to estimate $w(t)$ from the knowledge of a time series of $u(t)$ and of $y(t)$. In practice, it is well known that under semi-arid or arid climates, ET is the main contributor to w. As a consequence, estimating w allows us to estimate the crop requirements ET.

4. PRACTICAL APPLICATION

4.1 The experimental setup

Digital tensiometers (Watermark, Irrometer Inc., California) in the range of 0-199 cbar were installed at different depths in the 0-45 cm layer of the soil profile during two seasons: i) the 2016 growing season (June through September) and ii) the 2018 growing season, in two orchards cropped with avocado (*Persea americana* Mill) in Lebanon.

4.2 Observer design and results

The proposed approach was applied to data obtained on the orchards described hereabove (cf. Fig. 1 to Fig. 6). The purpose was to provide online soil water monitoring in the root zone and determine crop water requirements using a proposed soil-plant water balance approach. The ultimate goal was to provide irrigation advisory on this crop to growers and farmers to better manage the limited available water resources.

The sensor's readings were converted from cbar in mm using (1) before being injected in the observer (11). The observer gain was chosen using a try and error approach using the 2016 dataset and applied without additional settings to the 2018 dataset. It is to be noticed that the available dataset is not noisy (cf. Fig. 2 and Fig. 5). Thus, it is expected the observer to be not very sensitive to noise and we can choose gains relatively high. In order to tune the observer, we decided to use an original optimization technique consisting in tuning K in such a way that the innovation – using one dataset – is minimized. It was checked a posteriori that the obtained observer was stable. Stabilizing gains used to obtain the results presented below were $[18\quad 400\quad 1800]^T$ corresponding to closed loop poles of the observer - the system (11) arbitrarily placed at :

$[-6.11\quad -5.95+17i\quad -5.95-17i]^T$.

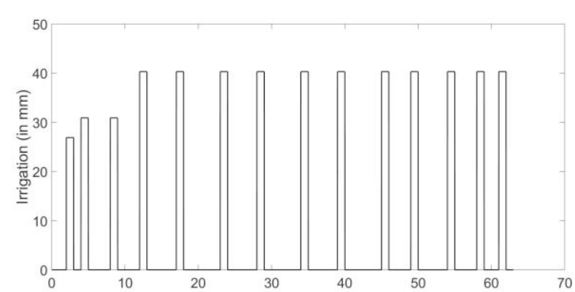

Fig. 1. Irrigation $I(t)$, in mm over time (in days) – 2016 dataset

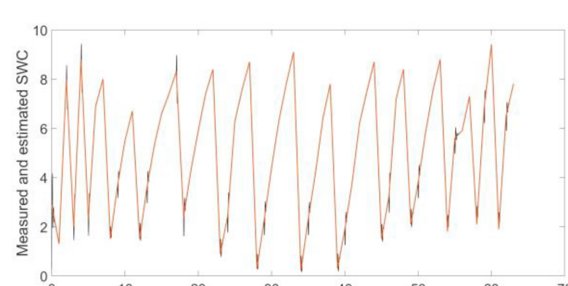

Fig. 2. Measured (in red) and estimated (in black) SWC, in mm over time – 2016 dataset

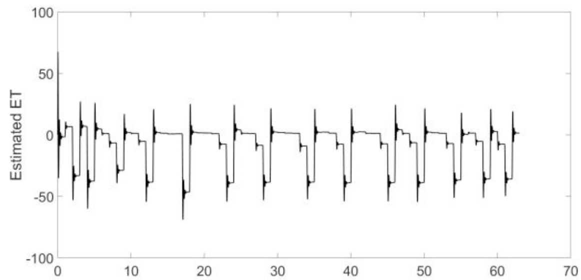

Fig. 3. Estimated evapotranspiration *ET*, in mm over time – 2016 dataset

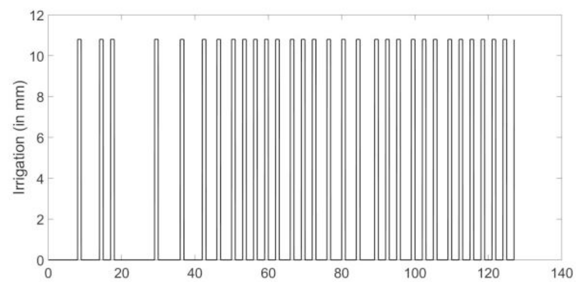

Fig. 4. Irrigation *I*(*t*), in mm over time (in days) – 2018 dataset

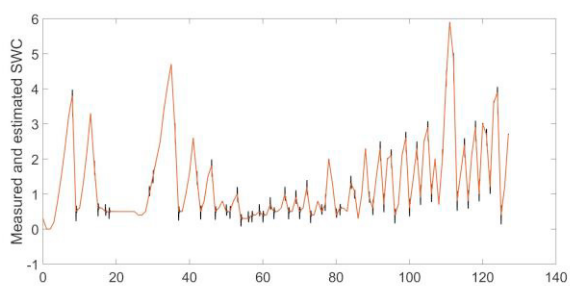

Fig. 5. Measured (in red) and estimated (in black) SWC, in mm over time – 2018 dataset

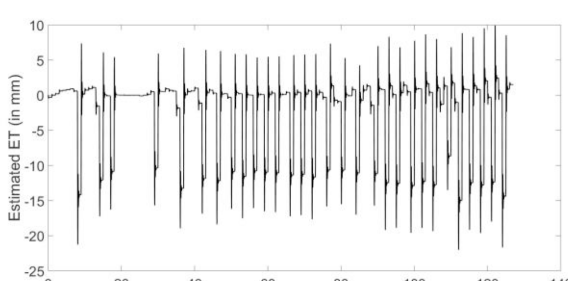

Fig. 6. Estimated evapotranspiration *ET*, in mm over time – 2018 dataset

First, whatever the dataset considered, it is to be noticed that because measured data are not noisy at all, choosing high gains guarantees a very fast convergence of the estimator towards the measured data of *SWC* (cf. Fig. 2). When analyzing Fig. 3 and Fig. 6, it is clear that the reconstructed signal $\hat{w}(t)$ is indeed made of piecewise constants and abrupt slopes modeling the response of the plant to irrigation periods. In other words, after each irrigation event, the response of the plant – view as a constant plus a straight line – has to be recalibrated as proposed with respect to model (9). Second, notice that the estimated signal $\hat{w}(t)$ is not only negative – while it is actually supposed to give an estimation of the sum of all negative contributions to the dynamic of *SWC*. There are several possible explanations. Either measurements or the input signal are a little bit biased. Having chosen high gains for the observer, there are some overshoots including negative estimations of *SWC* while it should be constrained to be positive. Globally however, the results are good and very interesting from a practical viewpoint: using an observer for estimating *ET* is very innovative and useful for users.

5. DISCUSSION AND CONCLUSIONS

Results obtained within the frame of this study showed that soil sensing was quantitative and accurate method, since it is based on online readings of the soil water potential at different depths of the soil profile, and convert the readings into water depth (in mm) that are used by the soil-plant balance through the proposed equation.

Results also showed that the proposed approach was good in simulating the dynamic of soil water content (*SWC*) in the root zone as the sum of two components of the soil-plant water balance; the first negative with unknown outputs (*ET*, D_r and R_o) and the other positive with known inputs (*P* and *I*). The goodness of the proposed approach depends on the availability of input variables and the estimation of unknown outputs. In other words, the proposed approach behaved as a 'watcher' of the different components of the soil-plant water balance system. It was demonstrated that when SWC is monitored at a regular basis, it becomes feasible and reliable calculating *ET*, being the major unknown output in this complex system.

On the other hand, the calculations of *ET* made with the proposed 'watcher' approach accounted for the net irrigation requirments of avocado during the growing season from June throughout September. Net irrigation requirements of avocade (the integral of $\hat{w}(t)$) were found to as much as 622 mm for the 2016 dataset while it was 380 for the 2018 dataset (to be compared to the volumes of water that were brought and that were 532 mm and 324 mm respectively for both years). This finding helps optimizing irrigation supply by providing guidelines to growers and farmers on sustainable water management for this crop under Lebanon's Mediterranean climate and water resources limitations.

Further validation of the proposed approach is still needed on other crops and different environments. For future works, we suggest calculating net irrigation requirements assuming a threshold level of *SWC* as a fraction of the total available water in the soil at a desired depth.

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