Using plant water status to define threshold values for irrigation management of vegetable crops using soil moisture sensors

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Abstract

Thresholds of soil matric potential (SMP) and available soil water content (AWC) required to prevent water limitations between irrigations were determined for bell pepper, melon, and spring and winter tomato grown in Mediterranean-type greenhouses on the south-eastern coast of Spain. Thresholds were identified by measuring the divergence of leaf water potential of un-watered plants from that of well-watered plants. Soil matric potential thresholds were –58 kPa for pepper, –35 kPa for melon, and –38 to –58 kPa for tomato. In general, SMP thresholds were more negative under lower evaporative demand conditions such as during autumn and winter months. Available soil water content thresholds, for a given crop and drying cycle, differed appreciably depending on soil depth and the method used to calculate the values. For the four crops studied, AWC thresholds calculated at 0–40 cm were 13–15% higher than those calculated at 0–20 cm. Each AWC threshold for 0–20 cm depth was 21–29% lower when AWC was based on laboratory rather than field determinations of field capacity and permanent wilting point. For a given method of calculating AWC, AWC threshold values were similar for different crops and drying cycles, suggesting limited sensitivity of the AWC approach. Using the manufacturer’s calibration, the capacitance sensor used for SWC measurements overestimated SWC by an average of 36%. An in situ calibration provided generally good agreement with the actual SWC between 0.15 and 0.22 cm³ cm⁻³; however, for higher SWC values, the in situ calibration underestimated SWC. The results of this study demonstrated the uncertainty of using recommended fixed AWC threshold values for irrigation management, using SWC sensors, because of issues related to the definition of rooting depth, measurement of FC and PWP, sensor calibration, and sensor accuracy across the relevant range of water contents. These data suggest that SMP thresholds are much more reliable than AWC thresholds for scheduling irrigations in greenhouse-grown vegetable crops. Technical issues regarding on-farm measurement of SMP and SWC are discussed.

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1. Introduction

Intensive vegetable production systems are commonly located in warm climatic regions, such as the Mediterranean coast, because growing conditions are favourable for numerous vegetable species. Irrigation is required to ensure a continuously adequate water supply. These regions commonly have limited fresh water resources, and experience increasing competition for limited water resources from tourism and housing development. Many fresh water resources have been degraded by agricultural activity, through over-exploitation, contamination with nutrients and salinisation (Gardner, 1993; Fereres et al., 2003). Consequently, there is considerable pressure on vegetable growers, in these regions, to optimise their use of irrigation water because of limited availability and to minimise adverse effects on local fresh water resources.

The greenhouse-based vegetable production system located along the south-eastern Spanish Mediterranean coast, consisting of more than 37,000 ha of greenhouses (Castilla and Hernández, 2005), with 27,000 ha in the province of Almería alone (Castilla and Hernández, 2005), provides an example of the previously-mentioned issues. Currently, 80% of cropping is conducted in soil, and drip irrigation is used on all farms (Pérez-Farra and Céspedes, 2001). Most irrigation water is obtained from over-exploited local aquifers (ITGME, 1991). Other impacts on the local aquifer system include contamination with nitrate and pesticides, a rapidly rising water level in a superficial aquifer, salinisation and saltwater intrusion (Pulido-Bosch et al., 1997, 2000; Pulido-Bosch, 2005). Three of the major crops in this horticultural system are fresh market tomato, bell pepper and melon. Tomato and pepper are transplanted in summer/early autumn and grown through autumn and winter, with tomato sometimes continuing until early summer. Tomato and melon are grown as spring/summer crops.

Irrigation scheduling is generally based on experience (Fereres, 1996; Fereres et al., 2003), and it is generally accepted that farmers and vegetable growers over-irrigate to ensure that water is not limiting production. The scientifically based irrigation scheduling methods most suitable for vegetable production are the FAO method of estimating crop water requirements (Allen et al., 1998) and soil moisture sensors. Given the variable nature of vegetable production through differences in farm management, crop varieties and soil type, the FAO method can be considered as providing general guidelines. Soil moisture sensors potentially provide the means to irrigate in accordance with the unique characteristics of a given crop in a given field. These sensors can be used as a “stand-alone” method, or their use can be combined with the FAO method, or they can be used to complement irrigation management based on experience.

Soil moisture sensors measure either soil water matric potential (SMP) or volumetric soil water content (SWC). While tensiometers are probably the most commonly used SMP sensor on commercial farms, granular matrix sensors are widely available and have a number of favourable technical characteristics for on-farm use (Thompson et al., 2006). A variety of dielectric sensors, using time domain reflectometry (TDR) (Ferré and Topp, 2002) or capacitance (also referred to as frequency domain reflectometry or FDR) technologies (Starr and Paltineau, 2002; Fares and Polyakov, 2006), are available for on-farm measurement of SWC (SOWACS, 2002); with multiple depth capacitance sensors (Paltineau and Starr, 1997; Fares and Polyakov, 2006) probably being the most widely used for on-farm applications. Tensiometers, granular matrix sensors and capacitance sensors can be read manually or logged continuously, and can be used to automatically control irrigation systems. Critical to the use of both SMP and SWC soil moisture sensors is the threshold or lower limit value, which indicates the degree to which soil can dry before irrigation is required. Generally, threshold values are selected that ensure that crops do not experience water stress or a loss in production.

In practice, threshold SMP values are commonly recommended by Extension services, consultants or suppliers. Recommended SMP values appear to be based on experience and on a limited number of published scientific studies. Most published SMP threshold values for vegetable species are from agronomic studies comparing yields from treatments with different threshold SMP values (e.g. Bower et al., 1975; Smajstrla and Locascio, 1996). Most of these studies have been conducted with open field crops, and, for a given species, show a wide range of threshold SMP values, suggesting that site-specific factors were influential. For fresh tomato, reported SMP threshold values are −10 kPa in a fine sandy soil (Smajstrla and Locascio, 1996), −20 kPa in a clay loam soil (Bower et al., 1975), −30 kPa for loamy soils (Wang et al., 2005), and −60 to −150 kPa (Taylor, 1965; Hanson et al., 2000a). For pepper, reported SMP threshold values are −25 kPa (Smittle et al., 1994; Beese et al., 1982), −45 to −65 kPa (Hedge, 1988) and −100 kPa (Tedeschi and Zerbi, 1984). For melon, reported SMP threshold values are −35 to −40 kPa (Taylor, 1965; Hanson et al., 2000a) and −50 to −75 kPa (Pew and Gardner, 1983).

For SWC sensors, the concept of available soil water content (AWC) provides a practical framework for using SWC data for irrigation management. Threshold values of AWC (AWCₜ) have been estimated for many species and are listed in the relevant FAO manuals as allowable depletion factors (100 – AWCₜ) (Doorenbos and Kassam, 1979; Allen et al., 1998). Recommended FAO threshold values for AWC are: 70% for bell pepper and 60% for tomato and melon under conditions of medium evaporative demand (Allen et al., 1998), with a reduction of 20% of AWC for conditions of low evaporative demand.

Published AWC threshold values, from agronomic studies, for tomato, pepper and melon are generally higher than the FAO recommendations; Hartz (1993) reported values >80% for tomato, Jaimez et al. (1999) values of 68–80% for pepper, and Pellittero et al. (1993) values of 85–90% for processing pepper. Several authors (Sadras and Milroy, 1996; Sinclair et al., 1998; Girona et al., 2002) have commented upon the uncertainty of using fixed threshold values of AWC for irrigation scheduling or modelling studies; because for a given species, many factors such as soil characteristics, evaporative demand, or root distribution can affect AWC threshold values.

Identification of threshold values of soil moisture for irrigation management, either as SMP or AWC, using plant water status ensures the maintenance of soil moisture conditions that avoid physiological stress. This approach is likely to be more sensitive than assessing differences in production. To achieve statistically significant effects on yield in field studies, it is likely that the stresses would need to be
2. Materials and methods

2.1. Location and cropping details

The experimental work was conducted in four consecutive crops grown in a greenhouse at the field research station “Las Palmerillas”, of the Cajamar Foundation, in El Ejido, Almería province, in south-eastern Spain (24°38’S, 36°48’N and 151 m elevation). The plastic greenhouse measured 28 m long × 22.2 m wide; it was unheated, and passively ventilated. It was aligned with an east-west orientation. In each experiment, a vegetable crop was grown inside the greenhouse under similar conditions to commercial vegetable production on the south-eastern Mediterranean coast of Spain; the crops grown were bell pepper, melon, winter tomato and spring tomato.

The soil within the greenhouse was an artificial layered soil, as is commonly used in greenhouses in the region (Castilla et al., 1986; Castilla and Hernández, 2005): it was formed by placing a 20 cm layer of sandy loam soil, imported from a quarry, over the original stony, loam soil. A 10 cm layer of coarse river sand was placed over the imported sandy loam soil as a mulch. The imported sandy loam soil had 1.0% organic carbon and a pH (1:1, water) of 8.2. Soil bulk density values were 1.5 and 1.6 g cm$^{-3}$ for, respectively, the 0–10 and 10–20 cm depths in the imported soil, and 1.4 g cm$^{-3}$ for the 20–30 cm depth in the underlying original soil. Electrical conductivity (EC) measurements in saturated extract are commonly 1.2–2.0 dS m$^{-1}$ for both soils. The dominant clay mineral in each soil is illite. Drip irrigation tape was placed on the surface of the sand mulch with 1.5 m spacing between drip lines and 0.5 m spacing between emitters within drip-lines; the emitters had a discharge rate of 2.6 l h$^{-1}$. The irrigation water had an electrical conductivity of 0.4 dS m$^{-1}$. Nutrients were applied through the irrigation system, in accordance with local practice.

Bell pepper (Capsicum annuum L. cv. ‘Vergarsa’) was grown from 18 July 2002 to 13 February 2003, melon (Cucumis melo L. cv. ‘Sirio’) from 21 February to 25 June 2003, winter tomato (Lycopersicum esculentum L.; cv. Boludo) from 13 August 2003 to 16 January 2004, and spring tomato from 23 January to 6 July 2004. Pepper plants were grown in double-rows, with 0.5 m spacing between adjacent plants within each row, 0.4 m between rows in each double-row, and 1.1 m between the closest rows in adjacent double-rows, giving a plant density of 2.6 plants m$^{-2}$. Drip tape was positioned midway between the two rows of each double-row of pepper, with one dripper adjacent to one plant in each row. Melon and tomato plants were grown in single rows 1.5 m apart and 0.5 m spacing between plants giving a plant population of 1.33 plants m$^{-2}$. A drip irrigation emitter was located adjacent to and 8 cm from each plant. Plants were vertically supported by nylon cord guides, and pruned and managed following local practices.

During warmer periods, whitewash (suspension of calcium carbonate) was applied to the greenhouse roof to reduce the temperature inside the greenhouse. Whitewash was applied before transplanting the winter tomato and was removed on 16 September 2003. During the spring tomato crop, the whitewash was applied on 8 April 2004, and a second application was made on 17 May 2004; the whitewash was maintained until the end of the crop. Whitewash was not used with the pepper and melon crops. The use of whitewash in these studies was consistent with local practice.

One or two drying cycles were applied to each crop. Each drying cycle consisted of a well-watered control treatment, irrigated with 100% of estimated crop water requirements calculated using a mathematical model of crop evapotranspiration (ET$_{c}$) developed for vegetable crops grown in Mediterranean-type greenhouses (Orgaz et al., 2005), and an un-watered treatment in which no irrigation was applied. All drying cycles were applied during the fruit production phase. The dates of the drying cycles are given in Table 1. For the pepper and melon crops, one drying cycle was applied (Table 1). In each of the winter and spring tomato crops, two drying cycles were imposed (Table 1). Before and after the drying cycles, the crops were optimally irrigated as described for the well-watered treatment.

The greenhouse was divided into 12 experimental plots, with 6 plots on either side of a central passage. Plots on the southern side of the greenhouse measured 10.5 m × 4.5 m, and plots on the northern side measured 8.5 m × 4.5 m. There were three lines of irrigation drippers in each plot. In the melon and tomato crops, there were three rows of plants per plot, and in the pepper crop, there were three double-rows of plants per plot. Adjacent plots were partially hydraulically separated by vertically placing plastic sheeting to a depth of 30 cm from the...
surface of the imported soil. In each crop, only 8 of the 12 plots were used to apply the two irrigation treatments (4 plots for the well-watered and 4 plots for the un-watered). The experimental design for each treatment period was a randomised block design within four blocks (two in the northern side, and two in the southern side of the greenhouse), with the two irrigation treatments randomly allocated to each block.

### 2.3. Measurements

In the four crops, soil water status was measured in well-watered and un-watered plots as soil matric potential (SMP) and volumetric soil water content (SWC). Soil matric potential (SMP) was measured with granular matrix sensors (model Watermark 200SS, Irmrometer Co., Riverside, CA, USA) every 30 s, with the data averaged and then recorded every 30 min with a data logger (model CR10X, Campbell Scientific International, Logan, UT, USA). The Watermark sensors were positioned so that the mid-point of the sensor body was at 10 cm soil depth relative to the surface of the imported soil. In the pepper crop, each Watermark sensor was 14 cm from the emitter (perpendicular to the drip line), and 8 cm from emitter and plant in the direction parallel to the drip line. In melon and the two tomato crops, the corresponding distances were 6 and 8 cm. Watermark readings were initially converted to SMP using the equations of Allen (2000). Because of the inaccuracy of the Watermark sensor in rapidly drying soil (Thompson et al., 2006), SMP values determined with the Watermark, were subsequently corrected in relation to SMP measured with tensiometers (model SKT 600/IE, Skye Instruments, Llandrindod Wells, Wales, UK) that were recorded every 5 min and logged every 30 min using a data logger (model Datalog 2, Skye Instruments, Llandrindod Wells, Wales, UK). A unique relationship between SMP measured simultaneously with the Watermark sensors and with tensiometers was derived for each drying cycle. The tensiometers were located at the same distance from the plant and dripper as described previously for Watermark sensors and tensiometers. Volumetric soil water content measurements were made and recorded every 30 min on a data logger (model RT6, Sentek Sensor Technologies, South Australia, Australia) from the 0–10, 10–20, 20–30 and 30–40 cm soil depths relative to the surface of the imported soil. Volumetric soil water content (mm) was calculated for the 0–20 and 0–40 cm soil layers.

In the two drying periods in the spring tomato, SWC was measured with a TDR system (model Trase 600SX1, Soil Moisture Corp., Santa Barbara, CA, USA); measurements were made every day from Monday to Saturday at 9:00 h. Twenty centimeter-long TDR waveguides were installed vertically in the 0–20 cm soil layer at an equivalent position from the plant and dripper in each replicated plot as for the other sensors used. The manufacturer’s standard calibration was used to convert TDR readings to SWC as previous work had confirmed its accuracy in the same soil (Fernández et al., 2004).

The performance of the manufacturer’s default calibration equation for the capacitance sensors was evaluated during the spring tomato–spring drying cycle by comparing daily measurements made with capacitance sensors and the TDR. The manufacturer’s calibration is SF = 0.1957 × SWC^{0.404} + 0.02852, where SF is the scaled frequency which is calculated from readings of individual sensors made in PVC access tubes in the field, submerged in a bath of water or in the air, as described by Paltineanu and Starr (1997). The capacitance sensors were then calibrated for the 0–20 cm soil layer, using SWC measured with the TDR probes as reference values, during the spring tomato–spring drying cycle. The derived calibration equation was based on a linear relationship of SWC to SF values. To assess the accuracy of the derived in situ calibration equation, SWC data measured with the capacitance sensors were compared with TDR data measured simultaneously in the spring tomato–summer drying cycle. The derived in situ calibration equation was used for all SWC data obtained with the capacitance sensors for the 0–20 and 20–40 cm soil depths for all drying cycles. A previous calibration study, in a nearby greenhouse with the same soils, demonstrated that the same calibration equation for the capacitance sensor could be used for both the 0–20 and 20–40 cm soil depths (Fernández et al., 2004).

Available soil water content (AWC) was calculated for the 0–20 cm soil depth and for the 0–40 cm soil depth from SWC data as

\[
AWC = \left( \frac{SW_{C_{A}} - SW_{C_{PWP}}}{SW_{C_{FC}} - SW_{C_{PWP}}} \right) \times 100
\]
Where SWC is the volumetric soil water content expressed in millimeters, and the subscripts A, FC and PWP correspond to, respectively, the actual measured water content, field capacity and permanent wilting point. The two soil depths of 0–20 and 0–40 cm were evaluated because of conflicting information regarding root depth of vegetable crops grown in these soils. González (2003) reported that 85% of root length and mass were in the 0–20 cm soil depth, which corresponded to the layer of imported soil; whereas Castilla et al. (1986) reported that 60% of roots were in 0–20 cm with an appreciably smaller but significant proportion of roots in the 20–50 cm soil depth. Visual observations from trench studies with tomato, in the experimental greenhouse, suggested nearly all roots were in the 0–20 cm soil depth (R.B. Thompson, unpublished data); however, water uptake has been observed from the 20–40 cm depth shortly after withholding irrigation (R.B. Thompson, unpublished data).

Available soil water content was calculated in two different ways: (i) using FC and PWP values determined in situ (AWC-in situ) and (ii) using values determined in the laboratory (AWC-lab) with a pressure plate using tensions of −0.03 and −1.5 MPa for FC and PWP, respectively, as described by Klute (1986). The soil used for the pressure plate determinations was air-dried, sieved to pass through a 2 mm mesh, and packed into 5 cm diameter and 2 cm deep rings at the same bulk density as in the field. Field capacity was determined in situ following the method described by Cassel and Nielsen (1986). For that, the sand mulch was removed from an area of soil of approximately 2 m² in the experimental greenhouse, the top 40 cm of sand mulch was removed from an area of soil of approximately 2 m² in the experimental greenhouse, Suggested nearly all roots were in the 0–20 cm soil depth (R.B. Thompson, unpublished data); however, water uptake has been observed from the 20–40 cm depth shortly after withholding irrigation (R.B. Thompson, unpublished data).

For both methods of determining AWC, SWC values for FC and PWP were calculated from gravimetric soil water content determinations for the corresponding soil depth, and bulk density determined for three soil depths (0–10, 10–20, 20–30 and 30–40 cm). Available soil water content based on FC and PWP values determined in the field (AWC-in situ) was calculated for the 0–20 and 0–40 cm soil depths, and AWC based on laboratory determinations methods (AWC-lab) for 0–20 cm. The bulk density value for 20–30 cm soil depth was used for the 20–40 cm soil depth.

Threshold values of soil matric potential (SMP) and plant available water content (AWCt) for each drying cycle were determined as the value at which leaf water potential (ψleaf) in un-watered plants started to diverge from that in well-watered control plants using linear regression analysis (Meyer and Green, 1981). Leaf water potential was measured during each drying cycle and for several days afterwards following the resumption of irrigation. Measurements of ψleaf were made, with a pressure chamber (model 3000, Soil Moisture Co., Santa Barbara, CA, USA), on recently fully expanded leaves that were well exposed to sunlight. These measurements were made every day Monday–Saturday between 12:00 and 14:00 h on four plants, one from each replicate plot.

Climatic parameters were continuously monitored within the greenhouse. Air temperature and relative humidity were measured inside the greenhouse with a ventilated psychrometer located immediately above the crop (model MTH-A1, ITC, Almería, Spain). These data were measured every 30 s, and 30 min average values were recorded with a data logger (model CR10X, Campbell Scientific Inc., UT, USA). Solar radiation was measured with a pyranometer (model SKS 1110, Skye Instruments, Llandrindod Wells, Wales, UK) installed at 2 m height, measurements were recorded every 30 min with a data logger (model H08-008-04, Hobo, Onset Computer Co., Bourne, Maine, USA). Reference evapotranspiration (ET0) was calculated for each drying cycle from solar radiation values using the calibration of the FAO-radiation equation developed for the plastic greenhouses of the south-eastern Mediterranean coast of Spain (Fernández et al., 2001; Orgaz et al., 2005). Statistical analyses were conducted with Statgraphics Plus Version 4.1. (Manugistic Co., Rockville, MD, USA).

### Table 2 - Climatic data averaged for each drying cycle for the four vegetable crops studied

<table>
<thead>
<tr>
<th>Climatic parameter</th>
<th>Pepper (pepper drying cycle)</th>
<th>Melon (melon drying cycle)</th>
<th>Winter tomato</th>
<th>Spring tomato</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Autumn drying cycle</td>
<td>Winter drying cycle</td>
<td>Summer drying cycle</td>
<td>Winter drying cycle</td>
</tr>
<tr>
<td>Average daily mean air temperature (°C)</td>
<td>12.5</td>
<td>22.6</td>
<td>21.9</td>
<td>13.3</td>
</tr>
<tr>
<td>Average daily mean VPD (kPa)</td>
<td>0.36</td>
<td>0.75</td>
<td>0.72</td>
<td>0.24</td>
</tr>
<tr>
<td>Average daily ET₀ (mm day⁻¹)</td>
<td>1.3</td>
<td>4.4</td>
<td>2.2</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Data are presented of: daily mean air temperature, daily mean vapour pressure deficit (VPD, kPa) and daily reference evapotranspiration (ET₀) inside the greenhouse.

### 3. Results

#### 3.1. Climatic conditions

There were considerable differences in climatic conditions between the different drying cycles, both between crops and between the two drying cycles in each of the two tomato crops (Table 2), reflecting the different periods of the year when the crops were grown and when the drying cycles were applied.

#### Table 2 – Climatic data averaged for each drying cycle for the four vegetable crops studied

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Data are presented of: daily mean air temperature, daily mean vapour pressure deficit (VPD, kPa) and daily reference evapotranspiration (ET₀) inside the greenhouse.
Average daily mean air temperatures were approximately 10°C higher and average daily mean vapour pressure deficit (VPD) was two to four times higher during the melon drying cycle, winter tomato–autumn drying cycle and spring tomato–summer drying cycle than during the drying cycles applied in winter (pepper; winter tomato–winter drying cycle). The spring tomato–spring drying cycle had intermediate values of temperature and VPD, and the spring tomato–summer cycle the highest values. Values of ET₀ reflected the period of the year when the drying cycles were conducted and the presence/absence of whitewash. The highest ET₀ values were observed for the drying cycle in the melon crop due to high values of solar radiation (data not shown) and the absence of whitewash, and were lowest for the winter tomato–winter drying cycle.

3.2. Evaluation and calibration of the capacitance system

The relationship between volumetric soil water content (SWC) measured with capacitance sensors using the manufacturer’s calibration and measured with the TDR system, for the 0–20 cm soil depth, is presented in Fig. 1a. Using this calibration, the capacitance sensor considerably overestimated SWC, the average overestimation being 36%. The slope of the regression line of 0.65 indicated that the overestimation was relatively larger at lower soil moisture contents and smaller at higher soil moisture contents. The subsequent in situ calibration of the capacitance sensors, during the spring drying cycle of the spring tomato crop, produced the linear regression equation of SWC = 1.1807 × SF − 0.6972, which was statistically significant (R² = 0.88, RMSE = 0.008 cm³ cm⁻³, n = 20) (Fig. 1b). The evaluation of the in situ calibration by comparison with SWC measurements made with the TDR system, during the summer drying cycle of the spring tomato, showed generally good agreement with respect to absolute values and trends (Fig. 1c). At the highest SWC values, of >0.26 cm³ cm⁻³, the capacitance sensor, using the in situ calibration, appreciably underestimated SWC.

3.3. Relationships between plant and soil water status

The evolution of ψ_leaf and soil matric potential (SMP) for the well-watered and un-watered treatments, and of available soil water content (AWC) for the un-watered treatment, calculated for both the 0–20 and 0–40 cm soil depths, for the drying cycle applied to the pepper crop, in winter under low evaporative conditions, is presented in Fig. 2. Differences in ψ_leaf between well-watered and un-watered plants, are apparent in Fig. 2a from 5 days after irrigation ceased, and were statistically significant (P < 0.05; ANOVA) from 8 days after irrigation ceased until its resumption (Fig. 2a). The increase in ψ_leaf between 7 and 10 February occurred during overcast days with low solar radiation (data not presented). Following the cessation of irrigation, SMP in the un-watered treatment decreased progressively to −115 kPa at the end of the drying cycle (Fig. 2b). Soil matric potential in the well-watered treatment was generally maintained between −10 and −30 kPa (Fig. 2b). Available soil water content for the un-watered treatment also decreased progressively reaching minimum values of 57% and 74% for, respectively, the 0–20 and 0–40 cm soil depths (Fig. 2c).

The linear regression analyses of SMP and AWC against relative ψ_leaf (ψ_leaf un-watered divided by ψ_leaf well-watered) to determine threshold SMP and AWC values for the pepper crop are presented in Fig. 3. The threshold SMP at which the reduction in relative ψ_leaf was initially detected, using this approach, was −58 kPa (Fig. 3a; Table 3). Threshold AWC values were appreciably affected by the soil depth used to determine AWC, with values of 71% for the 0–20 cm soil depth and 86% for the 0–40 cm soil depth (Fig. 3b; Table 3). These threshold AWC values were calculated using field measurement of field capacity (FC) and permanent wilting point (PWP).
Using AWC calculated with laboratory-determined FC and PWP values gave a much lower AWC threshold value for the 0–20 cm soil depth of 48% (Table 3).

In the conditions of much higher evaporative demand during the summer drying cycle in the spring tomato crop (Table 2), withholding irrigation had an earlier and stronger effect on plant and soil water status than was observed with the autumn-winter grown pepper crop. Differences in Cleaf between un-watered and well-watered plants were apparent from 3 days after irrigation ceased (Fig. 4a), and were statistically significant (P < 0.05; ANOVA) from 1 day later until the resumption of irrigation (Fig. 4a). Once irrigation was withheld, SMP decreased progressively in the un-watered treatment reaching minimum values of −154 kPa (Fig. 4b). In the well-watered treatment, SMP was generally maintained between −10 and −30 kPa with the exception of several days when problems with the pump of the irrigation system prevented intended irrigations (Fig. 4b). Available soil water content decreased rapidly during the first 10 days of the drying cycle; thereafter, there was a slower rate of decrease until the end of the drying cycle when the lowest values of 37% and 50% for, respectively, the 0–20 and 0–40 cm soil depths were measured (Fig. 4c).

The linear regression analyses of SMP and AWC against relative Cleaf (Cleaf un-watered/Cleaf well-watered) to determine threshold SMP and AWC values for the summer drying cycle of the spring tomato crop are presented in Fig. 5. The threshold SMP value, at which the reduction in Cleaf of un-watered plants was detected, using this approach, was −43 kPa (Fig. 5a; Table 3). As with the drying cycle in the pepper crop, the threshold AWC value was strongly influenced by the depth of soil used when determining AWC, with values of 70% for the 0–20 cm soil depth, and 84% for the 0–40 cm soil depth (Fig. 5b; Table 3). The threshold AWC value for 0–20 cm soil depth had a much lower value of 49% when estimated...
4. Discussion

The results of this study demonstrated some important considerations regarding the use of volumetric soil water content (SWC) sensors for on-farm irrigation scheduling when using the conceptual framework of available soil water content (AWC). For the experimental soil, the manufacturer’s calibration, for the capacitance sensor used, substantially over-estimated SWC. Threshold AWC values were appreciably influenced by the method used to measure field capacity (FC) and permanent wilting point (PWP). These issues have major implications for on-farm use of SWC sensors with recommended fixed threshold values of AWC, because site-specific in situ calibrations are inappropriate for most commercial farmers, and on commercial farms there are likely to be uncertainties regarding rooting depth and site-specific FC and PWP values.

Using the manufacturer’s calibration, the capacitance sensor appreciably overestimated SWC. There are differing reports regarding the general applicability of a single calibration equation with this capacitance sensor. Paltineanu and Starr (1997) developed a calibration equation that was suitable for several soils with appreciably different textures. In several studies conducted in the laboratory (Gardner et al., 1998; Baumhardt et al., 2000; Leib et al., 2003), capacitance sensors appreciably overestimated SWC using the manufacturer’s calibration. A field study conducted in the same soil, as the present study, reported that the manufacturer’s calibration over-estimated SWC by an average of 47% (Fernández et al., 2004).

Several factors such as soil salinity, soil organic matter, swelling 2:1 clays, bulk density and changes in soil temperature are known to affect the calibration of this capacitance sensor (Mead et al., 1995; Paltineanu and Starr, 1997; Baumhardt et al., 2000). We cannot fully explain why the manufacturer’s calibration was so inaccurate in the present study. The moderately high soil salinity levels characteristics of vegetable crops continuously irrigated with nutrient solution may have contributed; soil solution electrical conductivity (EC) values were generally 2.0–3.0 dS m\(^{-1}\), suggesting saturated extract values of approximately 1.0–1.5 dS m\(^{-1}\) (assuming a two-times dilution). Within these soil solution EC values, the capacitance sensor can be influenced by changes in soil salinity (Thompson et al., 2004). It is generally recommended that for research applications of dielectric sensors that in situ calibrations be conducted to enhance the accuracy of measurement (Starr and Paltineau, 2002), and it has been suggested that for on-farm irrigation management applications the manufacturer’s calibration may suffice (Leib et al., 2003). The present study, together with several other studies, suggests that substantial measurement errors can

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**Table 3 – Threshold values of soil matric potential (SMP\(_t\)) and plant available water content (AWC\(_t\)) for each crop and drying cycle**

<table>
<thead>
<tr>
<th>SMP(_t) (kPa)</th>
<th>AWC(_t)-in situ, 0–20 cm (%)</th>
<th>AWC(_t)-in situ, 0–40 cm (%)</th>
<th>AWC(_t)-lab, 0–20 cm (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pepper</td>
<td>–58</td>
<td>71</td>
<td>86</td>
</tr>
<tr>
<td>Melon</td>
<td>–35</td>
<td>79</td>
<td>93</td>
</tr>
<tr>
<td>Winter tomato</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autumn drying cycle</td>
<td>–42</td>
<td>81</td>
<td>94</td>
</tr>
<tr>
<td>Winter drying cycle</td>
<td>–59</td>
<td>74</td>
<td>88</td>
</tr>
<tr>
<td>Spring tomato</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spring drying cycle</td>
<td>–39</td>
<td>73</td>
<td>86</td>
</tr>
<tr>
<td>Summer drying cycle</td>
<td>–43</td>
<td>70</td>
<td>84</td>
</tr>
</tbody>
</table>

Threshold values correspond to when leaf water potential of un-watered plants began to diverge from that of well-watered plants using a linear model. AWC\(_t\) were determined for: (i) the 0–20 cm soil depth (AWC\(_t\)-in situ, 0–20 cm); (ii) the 0–40 cm soil depth (AWC\(_t\)-in situ, 0–40 cm) using values of field capacity (FC) and permanent wilting point (PWP) determined in situ; (iii) for the 0–20 cm soil depth using FC and PWP values determined in the laboratory.
occur, with this capacitance sensor, when using the manufacturer’s calibration. Should such measurement errors occur on a commercial farm, they could have major implications for irrigation scheduling when using recommended threshold values of AWC or SWC to initiate irrigation.

Once the capacitance sensor was calibrated for the experimental soil, measurement of SWC was generally accurate between 0.15 and 0.22 cm$^3$ cm$^{-3}$; however, for higher SWC values between 0.26 and 0.30 cm$^3$ cm$^{-3}$, SWC was markedly underestimated, suggesting a reduced response to more moist soil conditions. Similar observations were reported by Tomer and Anderson (1995) and Moreno (2003).

Irrigation management using SMP sensors is based on the use of recommended threshold SMP values to indicate when irrigation is required. The SMP threshold values determined in the present study were $\approx 35$ kPa for melon, $\approx 58$ kPa for pepper, and $\approx 39$ to $\approx 59$ kPa for tomato. A relatively high value is expected for melon because it is grown when evaporative demand is relatively high. The value for melon, from the present study, is consistent with the $\approx 35$ to $\approx 40$ kPa range recommended by Taylor (1965), and subsequently by Hanson et al. (2000a). The SMP threshold values for tomato obtained in the present study are higher than the $\approx 60$ to $\approx 150$ kPa range recommended by Taylor (1965), and subsequently by Hanson et al. (2000a), for field-grown tomato, but slightly lower than the values of $\approx 20$ to $\approx 30$ kPa reported for agronomic studies conducted in medium-textured soils in open field crops (Bower et al., 1975; Wang et al., 2005). Differences between SMP threshold values of the present and other published...
studies can be attributed to site-specific factors such as the shallow rooting depth in the present work (González, 2003), the lower evaporative demand of greenhouse compared to field-grown crops (Montero et al., 1985), and the higher sensitivity of leaf water potential compared to agronomic differences to detect differences. The threshold SMP value for pepper, in the present study, is within the range of values reported by Beese et al. (1982), Tedeschi and Zerbi (1984), Hedge (1988) and Smittle et al. (1994).

Threshold SMP for a given species is influenced by growth stage and evaporative conditions (Hanson et al., 2000a). In the present work, the threshold SMP values are from the fruit production phase. The fresh market vegetable crops grown in the present study, e.g. fresh market tomato, are indeterminate plants with a very short vegetative phase (of several weeks after cotyledon expansion) and a prolonged phenological stage of simultaneous vegetative growth, fruit formation and fruit growth that continues for much of the period of crop growth (Kinet and Peet, 1997). In the present study, an effect of evaporative demand upon threshold SMP values was observed. For tomato, threshold SMP was approximately –60 kPa under very low evaporative conditions (ETc of 0.8 mm day\(^{-1}\)) and was –40 kPa under appreciably higher evaporative conditions (ETc around 2–3 mm day\(^{-1}\) (Tables 1 and 2). The effect of climate on SMP is well established, with higher SMP threshold values being recommended for higher evaporative conditions (Hanson et al., 2000a). Soil texture can also influence threshold SMP values (Hanson et al., 2000a); in lighter textured soils, SMP threshold values would be somewhat higher than reported here.

The threshold AWC values determined depended on the method used to calculate AWC. The soil depth used to calculate AWC, and the method used to determine FC and PWP, had large effects on threshold AWC values. Considering all of the drying cycles examined, the threshold AWC calculated for the 0–40 cm soil depth was 13–15% higher than for the 0–20 cm soil depth. In many cropping situations, there is likely to be uncertainty about the depth of roots in the soil profile. Additionally, there will be uncertainty as to how to define the rooting depth, e.g. “what proportion of root mass or length in a given increment of soil depth is required for that increment to be included in the calculation of AWC?”.

Working with peach trees, Girona et al. (2002) demonstrated the effect of using different soil depths on the calculation of threshold AWC; when they used the maximum rooting depth, they obtained an unrealistic AWC threshold value of 94%. Similarly, in the present work, using an AWC value calculated using the maximum rooting depth of 40 cm gave threshold AWC values that are very high compared to published values for herbaceous crops (Sardas and Milroy, 1996).

In the present study, threshold AWC values estimated using AWC calculated from laboratory-determined FC and PWP values were much lower than when using FC and PWP values obtained in undisturbed field soil. Such differences in AWC values, for a given soil, will clearly affect the application of recommended threshold AWC values. The occurrence of appreciable differences between laboratory and field-determined values of FC and PWP, and consequently of AWC is well established (Sardas and Milroy, 1996; Girona et al., 2002). The method used to obtain AWC is an important consideration when the conceptual framework of AWC is used to apply SWC data to irrigation management. Considering that determination of FC and PWP in the laboratory often involves considerable disturbance of soil, field determinations of FC and PWP appear to be more representative of cropping conditions.

Threshold AWC values, based on AWC calculated for the 0–20 cm soil depth and using field-determined FC and PWP values, were 70–81%, which correspond to depletion factors of 19–30% of AWC. The threshold AWC values determined in the present study are generally higher than the general recommendations for vegetable crops in the FAO manuals (Doorenbos and Kassam, 1979; Allen et al., 1998). For example, in the FAO manuals, recommended AWC threshold values for tomato grown in winter with ETc rates of 1–1.5 mm day\(^{-1}\) are 45%, and approximately 50% in late spring with ETc of 3 mm day\(^{-1}\) (Allen et al., 1998). The difference between the threshold values obtained in the present study and the FAO recommendations may be attributable to the general nature of the FAO recommendations, and that the methodology used to identify thresholds in the present study, of using plant water status, is presumably more sensitive than the agronomic approach behind the FAO recommendations.

In the current study, differences in SMP threshold values were observed with different evaporative conditions for the same species; however, such differences were not observed with the AWC threshold values. The lack of such an effect is inconsistent with the FAO manuals (Doorenbos and Kassam, 1979; Allen et al., 1998). The reason may be the characteristics of the soil retention curve of the soil used, in which for the range of soil moisture examined, relative changes in SMP were larger than the corresponding relative changes in SWC, suggesting that SWC using AWC was a less sensitive measure of soil water status. The apparently reduced sensitivity of the capacitance sensor, in this soil, at higher soil moisture contents, may have been a contributing factor. Additionally, the larger volume of soil with a heterogeneous distribution of soil water measured by the capacitance sensor may contribute to an apparent reduced sensitivity compared to SMP sensors, which are making “point” measurements.

The current work was conducted with drip irrigation, which is commonly used with intensive vegetable production, particularly where water resources are limited. The location of soil moisture sensors in relation to both the dripper and plant will influence the actual SMP or SWC values measured, which has implications for the general applicability of threshold values from individual studies such as this and of recommended fixed values such as those in the FAO manuals and Hanson et al. (2000a).

In summary, the work reported in this paper has demonstrated uncertainties regarding the use of recommended fixed AWC threshold values for irrigation management on account of the effect on measured AWC values of: (i) the depth of soil used to calculate AWC; (ii) the method used to measure FC and PWP. Additionally, there can be appreciable errors associated with measurement of SWC using soil moisture sensors; a requirement for site-specific calibration would considerably increase the complexity of using SWC sensors for irrigation management in commercial farms. An alternative approach may be to use information on soil water
dynamics, derived from continuously measured SWC data, to determine in situ SWC threshold values for individual crops and fields. Such an approach would avoid the uncertainties associated with applying recommended fixed threshold values that have been obtained elsewhere, and with sensor calibration. Currently, there are no published studies that assess such an approach. The use of SMP threshold values for irrigation management appeared to be more straightforward; however, there are issues relating to sensor performance that affect the practical application of these sensors. The limited working range of tensiometers (approximately 0 to –80 kPa) can be a limitation for crops in rapidly drying soil, and growers tend to dislike them for their preparation and maintenance requirements. Granular matrix sensors overcome the mentioned shortcomings of tensiometers; however, their calibration is an important issue (Thompson et al., 2006), and they appear to respond slowly in rapidly drying soil (Thompson et al., 2006). As a general observation, the current state of the use of soil moisture sensors for irrigation management, appears to be that SWC sensors have favourable technical characteristics but that there are major issues associated with applying them to on-farm use using the approach of recommended threshold AWC values, and that SMP sensors can be readily used with recommended threshold values, but that there are technical issues that influence their suitability for on-farm use.

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