ESTIMATING EVAPOTRANSPIRATION BY CAPACITANCE AND NEUTRON PROBES IN A DRIP-IRRIGATED APRICOT ORCHARD

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SUMMARY

*This paper describes how a neutron probe (NP) and a multi sensor capacitance probe (MCP) can be used for monitoring the soil water content in order to develop a soil water balance and to estimate the evapotranspiration (ETc) of an apricot (*Prunus armeniaca *L.) crop. The van Genuchten model was applied to estimate water drainage below the active root zone, based on the measurements from both devices. Average crop evapotranspiration (ETc), estimated from the soil water balance for the whole period (17 months), was 1.6 and 1.5mm/day for NP and MCP, respectively, while the crop evapotranspiration calculated by the Penman-Monteith method (ETc-FAO) was 2.3mm/day. Drainage measured by both devices was negligible. The ETc measured by MCP was better correlated with the ETc measured by FAO methodology than with that corresponding to NP. A good correlation between the ETc values measured by NP and MCP was found. However, MCP permits continuous recording of the soil water content, is cheaper and less dangerous, while NP produces more accurate measurements than MCP.*

Accurate measurement of the soil water content is crucial for improving the way in which irrigation water and natural rainfall are managed. Crop yield is generally more closely related to soil-water availability than to any other soil or meteorological variable (Baier and Robertson, 1968; De Jong and Boostma, 1996; Miller *et al*., 2002).

The inefficient management of irrigation (e.g. the application of excess water) results in water and essential nutrients being transported through the soil profile to depths below the rooting zone. Such water and nutrient losses adversely affect not only environmental sustainability but also the economics of production. Therefore, minimizing these losses is important for efficient crop management practices (Stone *et al*., 1973; Molz, 1981).

Evapotranspiration (ET) is an important parameter for determining the irrigation requirements of fruit trees, especially in semiarid environments. The quantity of water to be applied depends, among other factors, on the soil type and the root depth (Doorenbos and Pruitt, 1977). Therefore, accurate measurements of the soil water content and continuous monitoring of the fate of applied water are required to minimize drainage and leaching losses below the relatively shallow root zone in trickle irrigation systems.

KEYWORDS / Apricot Tree / Capacitance Probe / Drip Irrigation / Evapotranspiration / Soil Water Balance /

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In semiarid environments, where water is scarce, it is necessary to determine exactly the crop water requirements at any given moment (García-Orellana *et al*., 2007). Water balance is a useful tool for evaluating crop evapotranspiration, water losses and water use efficiency in commercial crops (Flores and Ruiz, 1998). Evapotranspiration depends on both physiological and environmental factors (Barradas *et al*., 2005), and varies as a function of rainfall, irrigation, drainage, runoff, and water soil content variation (Cano *et al*., 1991). Therefore, measurement of the soil water content and drainage could provide a promising technique for precisely determining plant water requirements. Direct measurement of the soil water content is cumbersome and tedious, although several devices are available which may facilitate the task. The neutron probe (NP), based on neutron scattering, measures soil water content instantaneously, although systematic reading is necessary to characterize temporal variations in this parameter. Recently, new high performance measurement technology has been developed that provides quick precise data acquisition. For example, the multi-sensor capacitance probe (MCP) based on frequency domain reflectrometry (FDR) has simplified the soil water content measurements on temporal and spatial scales while providing acceptable accuracy (Fares and Alva, 2000; Starr, 2005).

The aim of this work was to develop water balance, using neutron and multi-sensor capacitance probes, to estimate the evapotranspiration (ETc) of an apricot crop in a Mediterranean arid environment.

Materials and Methods

Plant material and experimental conditions

The study was carried out from January 2001 to May 2002 in a 2ha apricot orchard (*Prunus armeniaca* L., cv. Búlida, on Real Fino apricot rootstock), planted in 1986 with 8×8m plant spacing, on a loamy soil located in the province of Murcia, Spain (37º52′N, 1º25′W; 340masl). The soil water content was measured simultaneously by neutron probe (NP), as described by Abrisqueta *et al*. (2001), and by multi-sensor capacitance probe (MCP) as explained below. Both devices measured volumetric soil water content and were previously calibrated (Mounzer *et al*., 2006).

The trees were irrigated by a single drip irrigation line per tree row, with seven on-line auto-compensating emitters per tree, set 1m from each other (starting 1m from the trunk), each with a flow rate of $4 l\cdot h^{-1}$. The estimated application efficiency of the emitters was 95%. The irrigation water amounts were scheduled weekly based on the reference evapotranspiration (ETc), determined by Penman-Monteith methodology (Allen *et al*., 1998) using data collected by an automatic meteorological station located in the orchard, multiplied by published crop coefficients (Doorenbos and Pruitt, 1977) and adjusted according to canopy size (Fereres *et al*., 1982).

Soil water content measurements by MCP and NP

The soil water content through a 0.5m soil profile was monitored using a multi-sensor capacitance probe (MCP, AquaSpy Group Pty Ltd., model C-probe) and a neutron probe (NP, Troxler Electronic Laboratories, NC, model 4300) placed within the wetted bulb of the second emitter (from the tree trunk) of three randomly selected trees. The trees were selected from areas with mean textural characteristics, as indicated in Plana *et al*., (2002). The neutron probe measurements were made once or twice per week. Soil water content at 0.10m depth was measured using TDR (Ruiz-Sánchez *et al*., 2005). The PVC access tube of each MCP was installed using a special auger to ensure good contact between the tube and the soil. The bottom of the PVC access tubes were plugged with a rubber compression plug to prevent the entrance of water and vapor. An intrusion plastic bus was used to hold the four sensors at their respective depths. The probes were connected through a 7-pin cable to a Radio Transmission Unit (RTU), which read the frequency response at each sensor and stored data every 15min. The stored data was sent to the laboratory via radio signal through a relay station. Each probe was fitted with sensors at 0.1, 0.2, 0.3 and 0.5m depth. The water content at 0.4m depth was calculated as an average of the data obtained at 0.3 and 0.5m. The two deepest measurements served to estimate drainage below the root zone.

Water balance model description

The model described below is based on the following assumptions: i) the soil profile is homogeneous, ii) soil water hysteresis is not a major factor in water movement under high frequency drip irrigation, iii) the wetted soil has a cylindrical shape (size: height 0.5m; diameter 0.52m), iv) the water flow is vertical, and v) there is no runoff and no capillary movement from deep groundwater. Thus, the soil water balance equation is

$$\text{Input} - \text{Output} = \text{Volume change} \qquad (1)$$

Inputs into the system are irrigation (I) and effective rainfall (R), while the outputs are drainage (Q), and evapotranspiration (ETc). Thus, the water balance for a unit area is

$$(I + R) - (ETc + Q) = \Delta W \qquad (2)$$

where ΔW: soil water content variation for a given period of time ($\Delta t = t_1 - t_2$), during which ETc is evaluated. All terms are in mm.

The soil water content variation between times t_1 an t_2 was measured as

$$\Delta W = \int_0^z \theta(z,t_1)dz - \int_0^z \theta(z,t_2)dz \qquad (3)$$

where z: depth of the root zone.

Continuous measurements of the soil water content also permitted the *in situ* determination of effective rainfall, which is equal to the variation in the soil water content shortly after a precipitation event.

If the water content and/or pressure head in and below the rooting zone are known for very short times, the soil hydraulic functions may be determined and, consequently, the drainage at depth z can be computed using

$$Q = -k(h)\frac{\Delta H}{\Delta z}\Delta t \qquad (4)$$

where k(h): unsaturated hydraulic conductivity ($cm\cdot h^{-1}$) at the pressure head h (cm) of the soil layer below the rooting zone, ΔH: hydraulic head variation between the bottom of the rooting zone depth and the next depth in the profile where the water content is monitored, and Δz: distance between the bottom of the rooting zone and the next depth in the soil profile where the water content is known. The total hydraulic head (cm) is defined as

$$H = h - z \qquad (5)$$

where z: depth below the soil surface (cm). Knowing the soil water content at a given location of the soil profile, the pressure head at that place can be determined by the following equation (Van Genuchten, 1980):

$$|h| = \frac{1}{\alpha}\left(\Theta^{-\frac{1}{m}} - 1\right)^{\frac{1}{n}} \qquad \Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad (6)$$

where s and r: saturated and residual values of the soil water content (θ), respectively, Θ: dimensionless water content, α: soil parameter approximating the air entering the soil, n: soil parameter related to the rate of desaturation, and m: soil parameter related to residual water conditions. To simplify subsequent notation, h in Eq. (6) is assumed to be positive. θ_r, θ_s and K_s were obtained by Abrisqueta *et al.* (2006) using the methods described by Trout *et al.* (1982). In this way, $\theta_r = 0.11 cm^3\cdot cm^{-3}$, $\theta_s = 0.36 cm^3\cdot cm^{-3}$ and $K_s = 0.132 cm\cdot h^{-1}$ and α, n and m, were determined empirically during the fitting procedure (Figure 1) with the expression

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha \times h)^n\right]^m} \qquad (7)$$

resulting in $\alpha = 5.347 \cdot 10^{-4}$, m= 0.750 and n= 1.294. The limits of Eq. (7) when $h \rightarrow \infty$ and when $h \rightarrow 0$ are residual water and saturated water, respectively. This simultaneous equation has been used previously to describe soil water relationships (Starsev and McNabb, 2001).

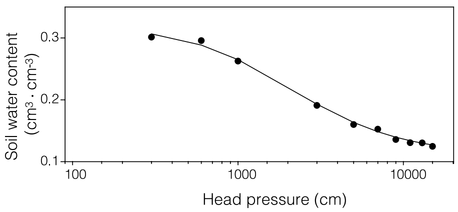

Figure 1. Head pressure and soil water content relationship in soil at the experimental site.

The relationship between the unsaturated hydraulic conductivity and the hydraulic head h(θ) was derived by Mualem (1976) as

$$k(h) = k_s \frac{\left[1-(\alpha h)^{n-1}\left[1+(\alpha h)^n\right]^{-m}\right]^2}{\left[1+(\alpha h)^n\right]^{\frac{m}{2}}} \quad (8)$$

where k_s: saturated hydraulic conductivity (cm/day).

Substitution of parameters α, n and m into Eq. (8) gives the unsaturated hydraulic conductivity k(h), which is considered drainage below the effective root zone. Substitution of the volumetric soil water content at the bottom of the effective root zone θ, as provided by MCP or NP in Eq. (6), gives the $|h|$ values. These are inserted in Eq. (7) to give the k(h) or drainage values.

Statistical Analysis

Estimated crop evapotranspiration (ETc) from the neutron and multi-sensor capacitance probe measurements and that obtained by FAO methodology were statistically evaluated by analysis of variance, squared chi and regression analysis to test the performance of both devices.

Results and Discussion

Soil water content measurements

The soil water inputs, rainfall and irrigation, were measured continuously during the experimental period (Figure 2). Total irrigation for the studied period was 727mm for 2001 and 158mm for 2002 (until June), while rainfall was 333.4mm in 2001 and 186mm in 2002 (until June). The wettest period ran from the end of September to the end of May, while both years there were completely dry summers. The heaviest irrigation provided was between June and August, with 60% of the total. Adequate irrigation during this post harvest period determines the fruit-yield potential of the following year in this crop (Ruiz-Sánchez *et al*., 1999; Torrecillas *et al*., 2000).

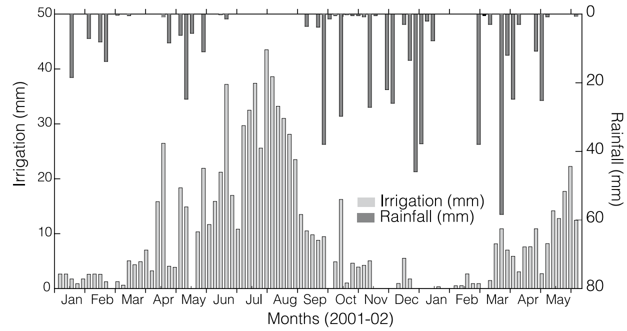

Figure 2. Irrigation and rainfall events during the experimental period.

The relationships between rainfall, irrigation, drainage and crop evapotranspiration modified the soil water content (SWC) in the topmost 0.50m soil layer (Figure 3). Measurements of the soil water content allowed comparison of the SWC determined by both techniques (NP and MCP). Both devices showed similar tendencies, although the MCP values were slightly higher. MCP behaviour is probably affected by temperature, as suggested by Steven *et al*., (2002) and Kelleners *et al*., (2004).

Although the SWC was highly dynamic during the experimental period (Figure 3), differences between the SWC values obtained with both probes remained consistent throughout, MCP showing an average SWC of 151mm and NP one of 132mm. Despite these differences, the two sensors showed a similar tracking. The SWC varied widely from 83 to 180mm, and both devices were able to detect this dynamic characteristic. This is an important point because the differences between the two sensors could have been due to the different performance level of the devices or the different soil volume explored by each, as was argued by Vera *et al*. (2007). Also, some environmental variables could have induced poor performance and led to inaccurate soil water content measurements (IAEA, 2000).

The lineal regression analysis of the soil water content measured by NP and MCP produced highly significant correlation and regression coefficients (0.6842*** and 0.4490*** respectively; Figure 4), which indicates that the measurements of both devices are strongly linked. By applying difference distribution analysis between both devices, it was found that there was a strong tendency for differences to decrease when the soil water content increased. So, when the volumetric SWC was between field capacity ($0.29 cm^3 \cdot cm^{-3}$; 147mm at 0.5m depth) and saturation ($0.36 cm^3 \cdot cm^{-3}$; 180mm at 0.5m depth), the differences between both devices were ±5%. Outside this range, the differences were greater. Both devices, then, behave similarly when the soil water content is near saturation.

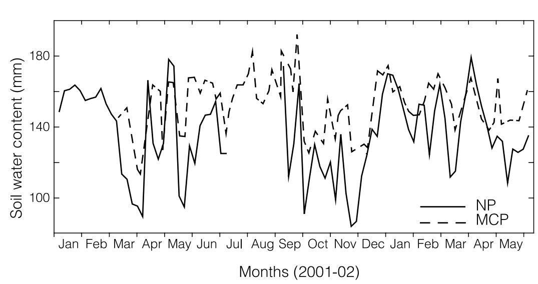

Figure 3. Soil water content at 0.5m depth measured by NP (continuous line) and MCP (interrupted line) in an apricot orchard during the experimental period.

Drainage was calculated using both devices at 50cm depth (Figure 6). NP showed 4.5mm of total drainage during the experimental period and MCP showed 2.1mm. Both values indicate that very little water was lost in this irrigation program, reflecting good irrigation water efficiency and the avoidance of percolation losses of water and agrochemicals (Kelleners *et al*., 2004). The pattern of water drainage was similar for both sensors, although NP values were higher than those of MCP on most dates. In general, the water losses in this study can be considered negligible due to the low value of the drainage losses.

Measured crop evapotranspiration (ETc)

The crop evapotranspiration (ETc) calculated by equation (2) using both devices and the same parameter estimated by FAO methodology (Allen *et al.,* 1998) resulted in a parallel behavior during the experimental period (Figure 5), although the analysis of averages com-

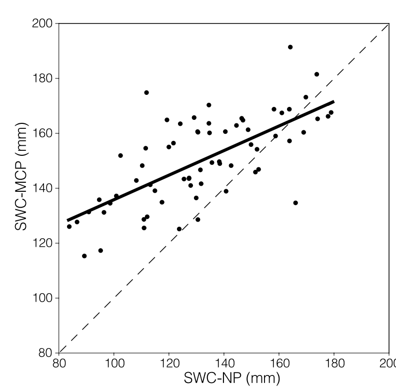

Figure 4. Soil water contents relationship (NP *vs* MCP).

parison identified statistically significant differences (Table I). FAO methodology showed significant higher values than NP and MCP but the two were not significantly different. The data of Table I agree with those reported by Abrisqueta *et al.* (2001), who found an average ETc of 1.95mm/day for well watered apricot trees. Note that for 2002 the ETc values corresponding to FAO methodology were higher than the corresponding NP and MCP values.

A chi-square test was used to check whether the NP, MCP and FAO methodology behaved similarly at any ETc value. For this, the ETc values were grouped into five intervals (ETc<1, 1≥ETc<2, 2≥ETc<3, 3≥ETc<4, and ETc≥4mm/day). The frequencies for each interval were compared for NP and MCP with the FAO methodology results (Table II). This test confirmed the results shown in Table I. Globally, NP and MCP were significantly different from FAO methodology, but significantly similar themselves. As regards the intervals considered, FAO methodology provided significantly different results from both devices only when the ETc values were <1mm/day (Table II).

Hence, in the case of apricot in this region, measuring ETc with NP or FDR devices will yield similar values and the selected device will depend on availability, the preference for uncomplicated risk-free measurements or the possibility of using telemetry for continuous measurements. Bell *et al.* (1987) reported that MCP offers an alternative to the neutron probe for measuring soil water content.

To compare the ETc values calculated by NP and MCP with FAO methodology, regression analysis was carried out (Table III). The MCP values best agreed with the FAO methodology values, with a 32% lower standard error, and a regression coefficient (0.88) close to unity. Given the narrow lineal relation between NP and MCP (Table III) it can be assumed that both devices behaved in a similar way.

Conclusions

The global average values of ETc calculated by soil water balance throughout the experimental period with both devices (NP and MCP) were statistically similar (1.62 and 1.53mm/day, respectively). The drainage measured by both devices was negligible (less than 5mm in the whole period). The ETc values calculated by MCP were better correlated with those calculated by FAO methodology than those provided by NP.

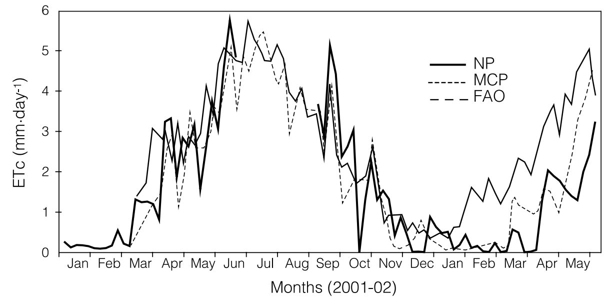

Figure 5. Crop evapotranspiration calculated by NP (continuous line) and MCP (dotted line) devices and by FAO (Penman-Monteith) methodology (interrupted line) in an apricot orchard during the experimental period.

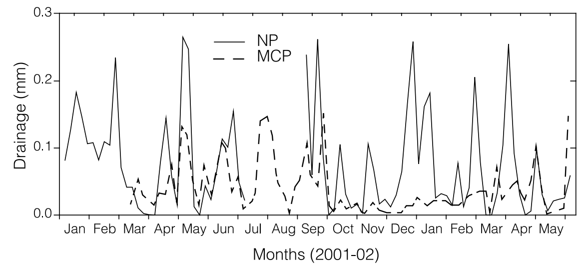

Figure 6. Drainage estimated by NP (continuous line) and MCP (interrupted line) devices in an apricot orchard during the experimental period.

TABLE I
ANALYSIS OF AVERAGES COMPARISON OF ETc VALUES CALCULATED BY NEUTRON (NP) AND MULTI-SENSOR CAPACITANCE (MCP) PROBES AND FAO METHODOLOGY IN AN APRICOT ORCHARD

	ETc (mm/day)		
Method	NP	MCP	FAO
Means	1.62 a	1.53 a	2.30 b
Standard error	±0.20	±0.17	±0.16

Means followed by different letters are significantly different according to Duncan's multiple range test.

TABLE II
CHI SQUARE TEST FOR ETc CALCULATED BY NP, MCP AND FAO METHODOLOGY IN AN APRICOT ORCHARD

	Frequencies			χ^2		
Intervals	FAO	NP	MCP	FAO/NP	FAO/MCP	NP/MCP
ETc<1	14	27	26	12.07***	10.29***	0.04 ns
1≥ETc<2	17	17	19	0.00 ns	0.24 ns	0.24 ns
2≥ETc<3	16	9	9	3.06 ns	3.06 ns	0.00 ns
3≥ETc<4	10	8	7	0.40 ns	0.90 ns	0.13 ns
ETc>4	9	5	5	1.78 ns	1.78 ns	0.00 ns
χ^2 Total				17.31***	18.97***	0.04 ns

ETc in mm/day, ***: probability level (P≤0.001), ns: not significant.

TABLE III
REGRESSION ANALYSIS OF ETc VALUES CALCULATED BY NP, MCP AND FAO METHODOLOGY IN AN APRICOT ORCHARD

Relation	Equation	r	P	SEE
NP *vs* FAO	$ETc_{(NP)} = 0.75ETc_{(FAO)} - 0.11$	0.6920	<0.0001	1.06
MCP *vs* FAO	$ETc_{(MCP)} = 0.88ETc_{(FAO)} - 0.49$	0.8580	<0.0001	0.72
MCP *vs* NP	$ETc_{(NP)} = 0.90ETc_{(MCP)} + 0.23$	0.8549	<0.0001	0.79

r: correlation coefficient, SEE: standard error of estimation, P: probability level.

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ESTIMACIÓN DE LA EVAPOTRANSPIRACIÓN POR CAPACITANCIA Y SONDAS NEUTRÓNICAS EN UNA PLANTACIÓN DE ALBARICOQUE IRRIGADA POR GOTEO

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RESUMEN

*En este trabajo se describe la forma en que un sensor de neutrones (SN) y una sonda multisensor de capacitancia (SMSC) pueden ser utilizados para el monitoreo del contenido de agua del suelo, a fin de establecer un balance hídrico de agua y estimar la evapotranspiración (ETc) en un cultivo de albaricoque (*Prunus armeniaca *L.). El modelo de van Genuchten fue aplicado para estimar el drenaje bajo la zona activa radical, con base en las mediciones hechas con los dos artefactos. La evpotranspiración promedio de la siembra (ETc), estimada a partir del balance de agua del suelo para todo el período (17 meses) fue de 1,6 y 1,5mm/día para SN y SMSC, respectivamente, mientras que la evapotranspitación calculada por el método de Penman-Monteith (ETc-FAO) fue de 2,3mm/día. El drenaje medido por ambos artefactos fue despreciable. La ETc medida con la SMSC resultó mejor correlacionada con la medida por la metodología de la FAO que aquella correspondiente al SN. Se encontró una buena correlación entre los valores de ETc medidos por SN y por SMSC. No obstante, la SMSC permite un registro continuo del contenido de agua del suelo, es más económica y menos peligrosa, mientras que el SN produce mediciones más precisas que la SMSC.*

ESTIMAÇÃO DA EVAPOTRANSPIRAÇÃO POR CAPACITÂNCIA E SONDAS NEUTRÔNICAS EM UMA PLANTAÇÃO DE DAMASCO IRRIGADA POR GOTEEJAMENTO

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RESUMO

*Neste trabalho se descreve a forma em que um sensor de nêutrons (SN) e uma sonda multisensor de capacitância (SMSC) podem ser utilizados para a monitoração do conteúdo de água do solo, a fim de estabelecer um balanço edáfico hídrico e estimar a evapotranspiração (ETc) em um cultivo de damasco (*Prunus armeniaca *L.). O modelo de van Genuchten foi aplicado para estimar a circulação de água sob a zona ativa radical, com base nas medições feitas com os dois artefatos. A evapotranspiração media da plantação (ETc), estimada a partir do balanço de água do solo para todo o período (17 meses) foi de 1,6 e 1,5mm/dia para SN e SMSC, respectivamente, enquanto a evapotranspiração calculada pelo método de Penman-Monteith (ETs-FAO) foi de 2,3mm/dia. A circulação medida por ambos os artefatos foi desprezível. A ETs medida com a SMSC resultou melhor correlacionada com a medida pela metodologia da FAO que aquela correspondente ao SN. Encontrou-se uma boa correlação entre os valores de ETs medidos por SN e por SMSC. No entanto, a SMSC permite um registro continuo do conteúdo de água do solo, é mais econômica e menos perigosa, enquanto que o SN produz medições mais precisas que a SMSC.*