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Quantitative analysis of soil water content in young drip-irrigated olive orchards

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Key words: evapotranspiration, neutron probe calibration, root density, stage of development.

Abstract: The present work was carried out in northern Tunisia (36°40' N, 10°16' E) during a single growing season in order to examine how water is distributed within young drip-irrigated olive orchards on the basis of distance to trunk and depth. Soil water content was measured by using a time domain reflectometer (TDR) and a neutron probe calibrated by concurrently measuring soil water content gravimetrically. Measurements were made below the canopies, along the line of drippers and out of the projected canopy area, at distances of 1.4 m, 2.2 m, 2.8 m and 4.2 m from trunks (Compartments G_1, G_2, G_3 and G_4), taking into account the heterogeneous distribution of roots. Results showed significant and positive correlations between the series of data collected simultaneously with the PVC and aluminium access tubes and those collected using the different methods and apparatus, demonstrating that any device may be employed, depending only on their availability. Results showed significant changes in soil water contents and stocks according to the season, depth and distance to trunk. During the rainy period, the stocks of water increased homogeneously within all soil compartments, but varied consistently during the dry season with lower values recorded within the upper soil layers. The area situated at 4.2 m from trunks was the driest in summer but it was the wettest during the rainy period. No roots were found at this distance while maximum root densities were observed at 0.4 m from trunk within the upper layers. The lack of water recorded after June affected tree height and fruit growth rates, although irrigation application was sufficient to meet the seasonal crop water needs.

1. Introduction

In Tunisia water resources (36 Km^3 annually) are mostly used to irrigate about 400 000 ha of annual and perennial crops. These amounts fulfill on average 75% of the crop water requirements (Hamza, 2009). In the north and center of the country, priority is always given to fruit trees and vegetables, although olive is considered the most important species and it is cultivated over a large area (1 700 000 ha).

Over the two last decades, the amount of available water has decreased consistently, thus the imbalance between water supply and water demand has intensified. This situation has given rise to much attention from the relevant authorities and the general public in terms of the average and long term water uses. Obviously, water should be used judiciously with reasonable amounts to meet water needs and without any wastage.

Determination of crop water needs, i.e. crop evapotranspiration (ETc), is therefore necessary to efficiently manage irrigation at the field level. However, it involves a highly complex set of processes which are influenced by watering conditions and tree and land cover characteristics. We have published in recent years technical papers (Masmoudi-Charfi, 2006; Masmoudi-Charfi *et al.*, 2006) presenting the water requirements of olive trees for different cultivation areas, according to age, soil coverage and growth stages based on the climatic method of the FAO (Allen *et al.*, 1998; Habaieb and Masmoudi-Charfi, 2003; Masmoudi-Charfi *et al.*, 2004). However, during the calculation procedure, we were confronted with a lack of information about the crop coefficient. In addition, long term climatic data were not available for all sites.

The lysimetric measurements give more precise information on water use, but is hard to carry out and expensive (Deidda *et al.*, 1990).

Estimates of actual evapotranspiration for adult olive trees were published in Tunisia and elsewhere for different environments (Ozyilmaz and Ozkara, 1989; Cohen, 1991; Pastor *et al.*, 1998; Michelakis, 2000; Musters and Bouten, 2000; Palomo *et al.*, 2002; Bandino and Dettori, 2003). These estimates require regular measurements of soil water content, which are essential to calibrate models estimating the vertical distribution of root water uptakes (Hazrat *et al.*, 2000; Palese *et al.*, 2000). Gravimetry is amongst the devices used to reliably measure soil water content (Hv) in the field. However, it is more useful for calibrating other devices than for scheduling irrigation because it takes a full day to dry samples and irrigation may be needed before the results of the measurements are obtained. The time domain reflectometer (TDR) is easy to use and reliable but the number of sites for measurements is limited. The neutron-scattering method was extensively used in field studies for measuring soil storage and its changes over

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time (Vachaud *et al.*, 1977; Evans *et al.*, 1996; Tarara and Ham, 1997; Xiong and Guo, 1999). With this apparatus, measurements can be made at different depths and sites, but these 'measurements' represent a property of the soil that can be related to soil-water content and are, therefore, indirect estimates (Hewlett *et al.*, 1964; Rana and Katerji, 2000). On the other hand, a survey of literature (Hewlett *et al.*, 1964; Vachaud *et al.*, 1977; Sinclair and Williams, 1979; Haverkamp *et al.*, 1984; Vauclin *et al.*, 1984; Villagra *et al.*, 1995) shows that little attention has been paid to the associated errors and uncertainties resulting from the definition of the calibration curve itself, when calibrating the apparatus. Instrumentation, timing and location variances are identified as the different components of the total variance of an individual water content estimate. Sinclair and Williams (1979) reported a comprehensive analysis of the contribution of instrument calibration and location variances to the variance of mean water content values and their changes in time. Implicitly they assumed that all the observations were independent of one another.

The present work illustrates, with results from a single growing season of a young olive orchard cv. Chétoui aged six years and cultivated in northern Tunisia, how water is distributed in such orchards taking into account time (stage of development) and root distribution. Our approach is based on estimating water content at different distances from trunks. Data were analyzed considering both spatial and temporal variability within different soil reservoirs, throughout the campaign and on some typical days. Specifically, the aim was to highlight the main difficulties found when measuring soil water content in drip-irrigated orchards characterized by discontinuous and low soil coverage.

2. Materials and Methods

Experiment site

The study was performed during a single growing season (2003) on a young olive orchard located at the experimental farm of the Institut National Agronomique de Tunisie, northern Tunisia (36°40' N, 10°16' E). The area is characterized by a Mediterranean climate with average annual water deficit of 750 mm and reference evapotranspiration (ET0) of 1200 mm. Weather variables were recorded continuously in a nearby automatic weather station. Daily average values were used for ET0 calculation (Table 1) following the Penman Monteith equation (Allen *et al.*, 1998).

Table 1 - Annual and seasonal (March - September) weather variables recorded in 2003

Weather variables	Value
Rainfall (mm/year)	790
Seasonal rainfall (mm)	346
ET_0 (mm/year)	1211
Seasonal ET_0 (mm)	982

The year of experiment was rainy and hot with annual and seasonal effective rainfall amounts of 546 mm and 239 mm, respectively. These values were estimated following the USDA method (FAO, 1976). Average maximum and minimum temperatures (24.9°C and 14.9°C, respectively) showed an increase of 3 and 7%, respectively, with regard to the average values recorded during the 25 previous years. Rising temperatures were noted during the three first months of the year, resulting in an increase of the growth degree day (GDD) of about 300 days.

Olive orchard

Three six-year-old olive trees (cv. Chétoui), representative of the whole orchard, were used in this experiment. They were planted at 6 m x 6 m spacing and stand on a textured clay-loamy soil of about 2 m depth. Soil characteristics were determined at the beginning of the experiment for each trench of soil to 1 m depth (Table 2). Average bulk density (d_a), soil water contents at field capacity (θ_{cc} measured at -0.3 MPa) and at wilting point (θ_{pfp} measured at -1.5 MPa) were 1.6 g/cm^3, 0.50 m^3/m^3 (50%) and 0.26 m^3/m^3 (26%), respectively.

Table 2 - Soil characteristics of the olive orchard

Horizon (cm)	0-20	20-40	40-60	60-80	80-100	Average	Ecartype
Clay %	39	34	28	22	20	29	7.1
Loam %	50	52	48	48	46	49	2.0
Sand %	11	14	24	32	34	23	9.3
d_a (g/cm^3)	1.55	1.64	1.60	1.60	1.68	1.61	0.04
θ_{cc} (%)	48	50	50	51	50	50	0.98
θ_{pfp} (%)	25	26	27	26	25	26	0.75

Trees were intentionally chosen of the same variety, with similar shape. Leaf area (LA) was determined after pruning by computing the number of leaves on representative branches and their specific area by planimetry (Fernandez and Moreno, 1999); individual average value of LA was 14 m^2. Soil coverage was low, rarely exceeding 35%. At the end of the campaign, mean tree height and canopy diameter reached 4.9 m and 4.0 m, respectively.

Water requirements and irrigation management

Average weather variables published in local papers (Masmoudi-Charfi, 2006) were used to estimate daily ET0 values. Crop evapotranspiration (ETc) was then determined following the FAO method for non-standard conditions (Allen *et al.*, 1998) as $ET_c = ET_o \times K_c \times K_r$, with a crop coefficient $K_c = 0.5$ (six-year-old trees) and Kr = 0.75 (COI, 1997) accounting for an average soil coverage of about 33% (Masmoudi-Charfi, 2008).

Trees were irrigated from 15 May to 5 September with amounts ranging between 0.333 m^3/tree and 1.098 m^3/tree according to the stage of growth. The seasonal irrigation amount was 5.4 m^3/tree. Periods and doses of irrigation are reported in Table 3. Water was supplied using four emitters per tree with a total discharge of 16 l/h. Fresh water was provided alternatively from the ‘Medjerda’ canal, the main river of northern Tunisia and nearby wells.

Table 3 - Irrigation supply periods and amounts (m^3/tree)

	1	2	3	4	5	6	7
Irrigation period	15-20/5	2-3/6	30/6-2/7	10-15/7	21-30/7	5-10/8	28/8-5/9
Irrigation amount	0.823	0.333	0.549	0.843	0.902	0.902	1.098

Field monitoring

Experimental protocol and soil water content measurements. This work was carried out in order to highlight the difficulties met at field level when elaborating protocols concerning irrigated olive orchards, characterized by heterogeneous distribution of light, soil coverage, roots and water application. Difficulties concerned mainly the choice of measurement sites and the right measuring device, particularly:

- At which depths, frequency and distances from trunks measurements should be taken?
- Which kind of apparatus and access tubes should be used for easy and precise soil moisture monitoring?
- Is there any relationship between measurements taken with different apparatus?
- How many repetitions (trees) are necessary to get significant results?
- What precautions should be taken when preparing and installing the access tubes and when calibrating the neutron probe?

Taking all these questions in mind, but also the results obtained for this same orchard relative to the root distribution (Masmoudi-Charfi and Ben Mechlia, 2011), a specific diagram was built in which the area surrounding the three olive trees was instrumented with access tubes covering all soil occupation cases. Figure 1 shows a series of 28 access tubes implemented vertically in the soil at distances from trunks ranging between 1.4 m and 4.2 m. Measurements of volumetric water contents (H_v,%) were carried out within this area from April to October at depths ranging from 0.20 to 1.20 m using a neutron probe (SOLO 25, Nardeux, France). Two types of tubes were experimented and compared. A correlation was then established between measurements made simultaneously with aluminum and PVC-polyamide tubes, which were locally assembled (4 cm inside diameter and 170 cm long). Specific glue was used to seal the components of the PVC-polyamide tubes in order to assure their tightness and impermeability to water. Neutron probe countings were coupled with routine observations of H_v made at the limit of the canopy (2 m from the trunk) on the eastern side of the medium tree, about 0.60-0.70 m from the emitters and 0.20, 0.40, 0.60, 0.80 and 1.0 m depth by using a time domain reflectometer (TDR) (Fig. 1).

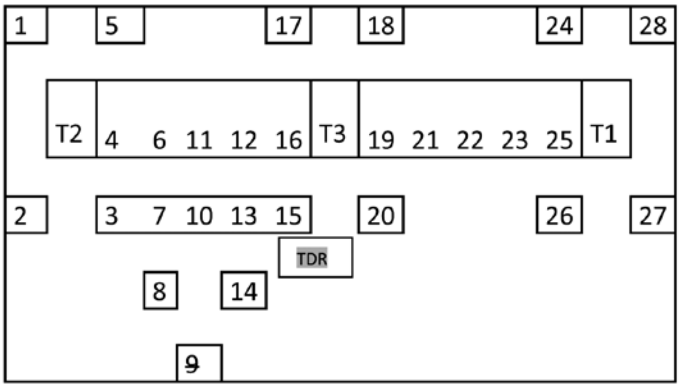

Fig. 1 - Distribution of access tubes for neutron probe measurements taking into account root distribution, soil humectation and soil coverage. Tubes were set around three olive trees of cultivar Chétoui at 1.5 m depth at distances of 1.4 m, 2.2 m, 2.8 m and 4.2 m from trunks.

The heterogeneous distribution of roots and discontinuity of the soil coverage make the interpretation of our measurements difficult. For this reason, four soil compartments designated G_1, G_2, G_3 and G_4 were considered according to the distance to trunk. The groups G_1 and G_2 include measurements of soil water content made below the canopy at 1.4 m and 2.2 m, respectively, with three and two replications. Observations made along the line of drippers at 2.8 m and out of the projected canopy area at 4.2 m belong to groups G_3 and G_4, respectively.

Probe calibration. Calibration of the neutron probe consists in relaying the count ratio (N/N_{water}) and the soil water content values determined for all depths exceeding 0.20 m by concurrently monitoring the probe countings and the gravimetric soil moisture. Measurements were made at the same sites, weekly, in dry and humid conditions to cover all potential values, and more frequently during the irrigation period. Before and after sampling, the counting was sampled in a water medium in order to control the possible drift in the electronic device provided by the probe itself. The average value was used to adjust the measurements made on the same day. Also, we have considered for each trench of soil a specific value of the bulk density (d_a) instead of using an average value for all soil layers, which may increase the error intervals. Finally, the series of data were correlated considering each trench of soil separately. The correlative equations were used to translate the counting values obtained during all the campaign into H_v estimates.

Soil water storage. Water stored in the soil was determined for each trench of soil and then for the whole profile to a depth of 1.2 m using the following equation: $S\ (mm) = 10 \times H_v \times D$, where D = is the layer depth (0.20 m), assuming a standard error of 0.02 m^3m^{-3} on H_v measurements.

Analyses of results. Soil water content values determined for each compartment (groups G_1, G_2, G_3 and

G_4) were analyzed separately considering two temporal scales. The first analysis was made during the campaign and the second concerned some typical days representing the main physiological processes that evolved during the growing season. The first date (29/5/2003), designated (S), coincided with the rapid fruit growth stage and it was dry, without any rain or irrigation supplies. The second date (16/7/2003) was chosen during an irrigation episode, corresponding to the stage of flower induction, designated (I). The third date (23/09/2003) was the period of fruit enlargement, designated (P). It corresponds to a high soil moisture period and was chosen after the first heavy rains (90 mm) of that autumn. Through measurements taken on these dates, we analyzed soil behavior under well- and low-watered conditions and different climatic demand.

3. Results

Calibration of the neutron probe

Count ratios (N/N_{water}) and soil water content values (H_v) obtained gravimetrically were positively correlated with r correlative coefficients (r) ranging between 0.69 and 0.83 for the portion of soil from 0.20 to 1.20 m depth (Fig. 2). The curves established for the four medium layers (20-40 cm, 40-60 cm, 60-80 cm, 80-100 cm), drawn with either the same or different values of bulk density, provided the same coefficient of correlation (r= 0.83, r= 0.76, r= 0.70 and r= 0.73 for 0.20-0.40 m, 0.40-0.60 m, 0.60-0.80 m, 0.80-1.00 m, respectively) for each soil layer. The trench of soil from 1.00 to 1.20 m showed some deviation with r= 0.69 when using a specific da value, and r= 0.66 when using an average value of da. These differences are due to transition between the clay-loamy and clay-sandy soil layers.

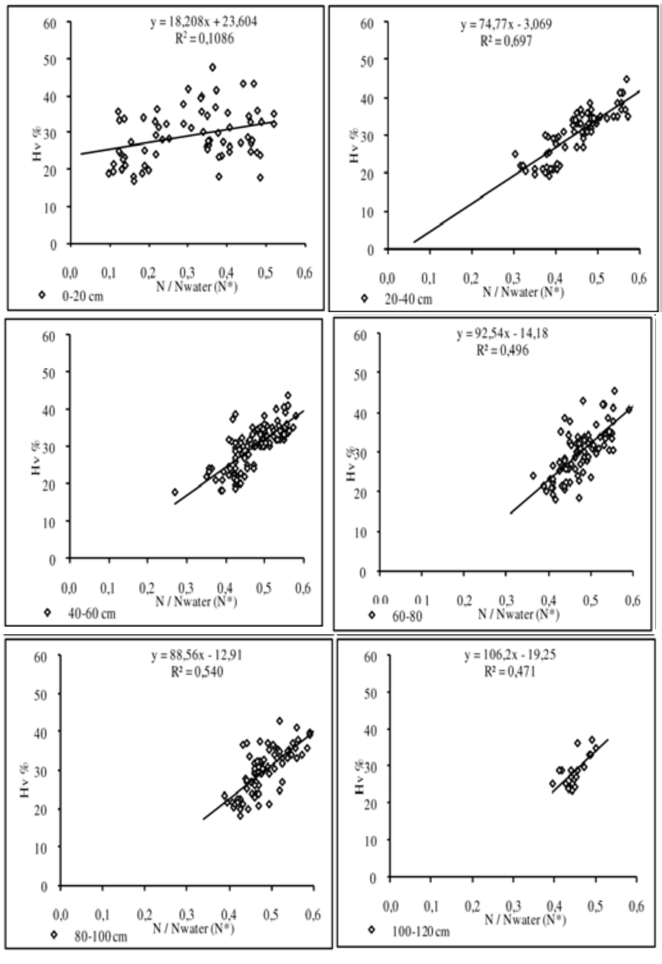

Fig. 2 - Probe calibration curves determined for the neutron SOLO 25 for different soil layers. Gravimetric measurements (H_v) were correlated to the counting ratio $N^* = N/N_{water}$, where N and N_{water} referred to counting made into the soil and water, respectively.

Relationships between TDR, neutron probe and gravimetric soil water content measurements

Measurements of H_v values taken using aluminum and PVC-polyamide access tubes were inter correlated, showing a positive and significant correlation curve with r = 0.73 (Fig. 3). The TDR-measurements were also correlated to the neutron probe estimates and to the gravimetric observations with high correlative coefficients of 0.87 and 0.79, respectively (Fig. 4). These results are of practical interest as they allow use of any apparatus or method with confidence depending on their availability. However, it is important to take into account the representativety of the measurements which could not be taken simultaneously every time at each location (the case of TDR).

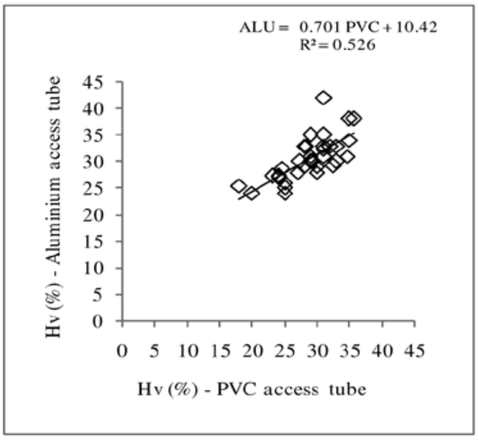

Fig. 3 - Relationship between H_v (%) measurements made simultanuously with the aluminium and PVC-polyamide access tubes.

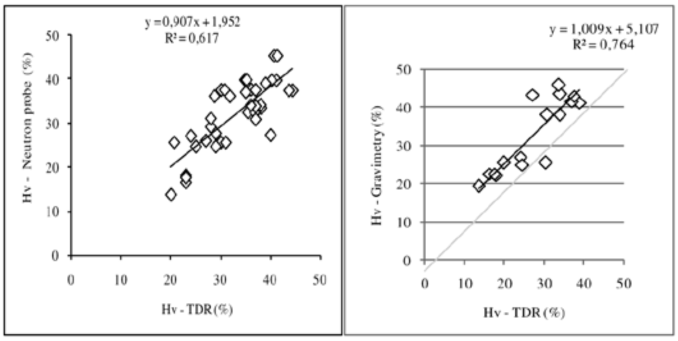

Fig. 4 - Relationships between H_v (%) measurements made simultanuously with TDR, neutron probe and gravimetry.

Spatio-temporal variability of soil water content

Soil water contents measured with TDR fluctuated during the growing season by 15 to 46% depending on depth, season and watering conditions (Fig. 5). During the irrigation period (beginning from 15 May), H_v-values ranged from 25 to 39% with maximum and minimum values observed within the medium depths and at the top soil layer, respectively. Resumption of irrigation at the end of August provided a significant increase of H_v values which decreased rapidly after mid October. The lowest values were recorded at the end of the year under low soil evaporation conditions and root activity, and specially in the upper layer.

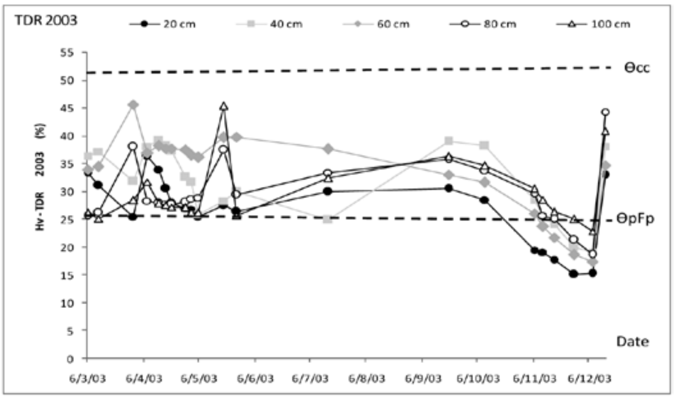

Fig. 5 - Evolution of the TDR-soil water content measurements according to depth in 2003.

Soil water content also varied according to the distance to trunk (Fig. 6). This was observed through estimates of water stocks determined throughout the campaign for all soil compartments (G_1, G_2, G_3 and G_4). Considerable variability was observed between these reservoirs with regard to soil humectation events (i.e. rainfall and irrigation supplies) with values between 225 and 400 mm.

The stock of water recorded at the beginning of the campaign (April) was close to 350 mm with little variability between soil compartments. It then decreased during the first decade of May in response to the increasing climatic demand and plant activity. The beginning of irrigation on 15 May marked the start of a consistent increase of the stocks around the emitters, enhancing the disparities between compartments. Values subsequently evolved continuously with a downward trend following water application. From mid July to the end of August, irrigation was interrupted, leading to a significant decline of these stocks, to reach their lowest value of 225 mm in G_4. Rainfall received in the autumn increased and homogenized the soil water status. The highest stocks were recorded in this case for G_1, while reservoirs G_3 and G_2 provided intermediate values; these areas were not subject to irrigation but they were partially shaded during the diurnal period (reduction of soil evaporation). Reservoir G4 showed the lowest stocks in summer, but it gave the highest values during the rainy period. These results indicate that soil water status mainly depends on depth, water application and distance to trunk, but it may vary depending on plant activity.

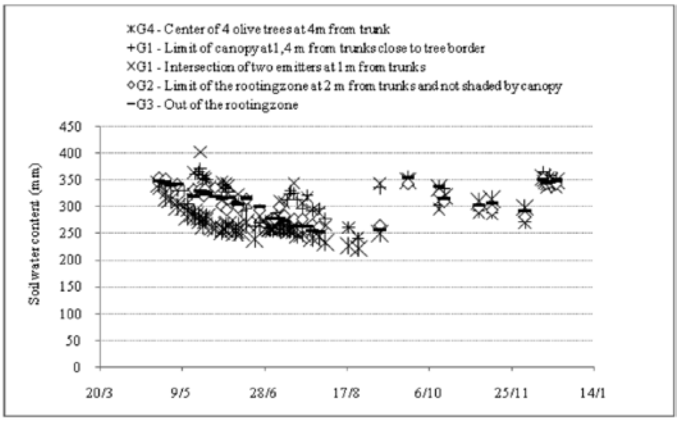

Fig. 6 - Soil water stocks (mm) determined for all the profile (0-100 cm depth) at 1.4 m (G_1), 2.0 m (G_2), 2.8 m (G_3) and 4.2 m (G_4) from trunks.

Soil water content and tree response

Root growth and canopy relationship. Roots extended rapidly during the growing season to reach in May the limit of the canopy at 2.12 m from trunks. Maximum root number was observed at 0.40-0.60 m depth (Table 4), i.e. at depths characterized by high soil water contents (Fig. 5), while maximum root densities (dr) were recorded in the top soil layers at 0.40 m from the trunks (Fig. 7). The highest value of dr (0.67 cm/cm^3) was observed in G_1. Then, as distance to trunk increased, root densities decreased, as did the stocks of water. At a greater distance from trunks (80 cm), maximum root densities ranged between 0.15 cm/cm^3 (deeper layers) and 0.35 cm/cm^3 (upper layers). During this same period, the canopy diameter increased at similar rates leading to equilibrium between the above- and underground areas, just a few years after planting. We recorded at the end of the campaign an optimum LA/L_r (leaf area/root length) value of 2.3 km/m^2 while the ratio S_r/S_c (root area/projected canopy area) approximated the unit (Table 5). This result indicates that as leaf area increased, the amount of carbohydrates increased allow-

Table 4 - Root distribution, number and diameter observed during the experimental year for six-year-old Chétoui olive trees compared with measurements made on five-year-old tree

Soil layer (cm)/Age	5-year-old tree	6-year-old tree
Distribution of roots		
0-20	9	51
20-40	5	91
40-60	3	116
60-80	5	97
80-100	3	81
100-120	0	36
Total number of roots	25	472
Maximum root diameter (mm)	24	27
Volume of the rooting system (cm^3)	5.3	11.2
Maximum distance to trunk (cm)	150	212

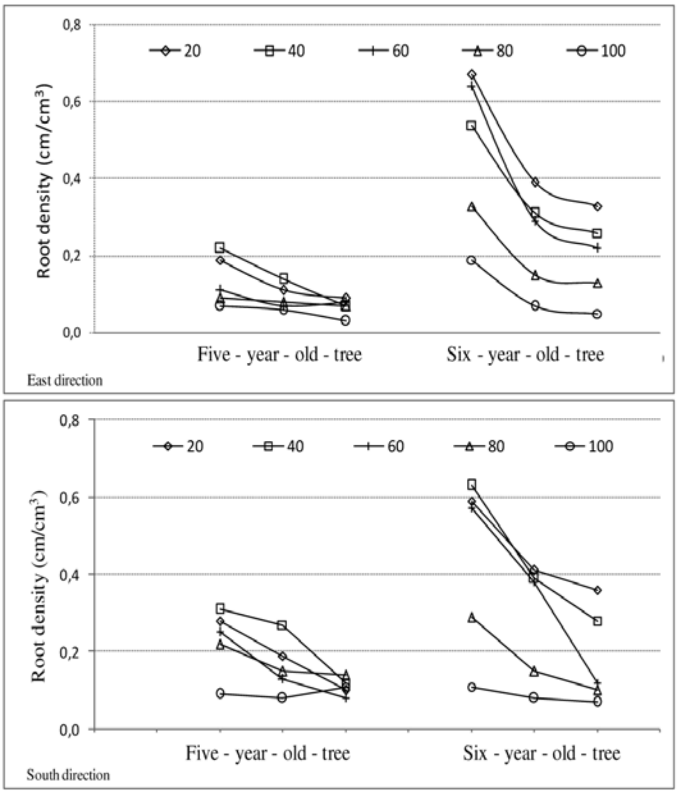

Fig. 7 - Average root densities (cm/cm³) recorded for five- and six-year-old olive trees at 0.40, 0.80, and 1.20 m distance from trunks. Measurements were made in both east and south directions at different depths (0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm).

Table 5 - Characteristics of the rooting system of the six-year-old-tree of cultivar Chétoui compared with those recorded for a five-year-old tree

Soil layer (cm)/Age	5-year-old tree	6-year-old tree
Root area (m²)	7.10	13.8
Projected canopy area (m²)	8.04	11.94
Root area (S_r, m²) / Projected canopy area (S_c, m²)	0.9	1.2
Maximum canopy radius (m)	1.60	1.95
Average root density (cm/cm³)	0.13	0.30
Length of the rooting system (km)	7.05	33.94

ing good development of roots and fruits. This hypothesis is analyzed in the following section through simultaneous monitoring of fruit growth and tree height.

Watering conditions, tree growth and fruit development. Growth patterns relative to tree height and fruit diameter observed in 2003 were different from those recorded for the previous year (Fig. 8). In 2002, tree height and fruit diameter increased with irregular rates, but continuously from April till October, peaking at 1.4 cm/day (105 DOY) and 0.22 mm/day (142 DOY), respectively. In the following year, we did not record any peak values for tree height but rather a low and constant rate of about 0.10- 0.15 cm/day. From April to June, fruits grew with increasing rates to peak at 0.29 mm/day on 155 DOY. Soil water contents recorded during this period of cell division and early fruit growth (10/4-10/6, 100-160 DOY) (Fig. 9) were apparently sufficient to assure suitable fruit development.

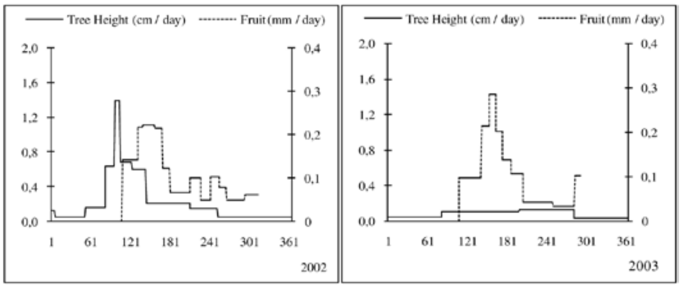

Fig. 8 - Growth patterns of olive tree height (cm/day) and fruit diameter (mm/day) recorded in 2003 compared to tree height and fruit development curves recorded in 2002. Values are averages of 96 tree height and 480 fruit diameter measurements made on Chétoui olive trees.

Tree height and fruit growth decreased significantly in July-August most likely because of interruption of irrigation and the decrease of soil water content values (Fig. 9). After this period of a lack of water, Hv-values increased particularly in the deeper depths, enhancing the ultimate fruit development (284 DOY, 0.1 mm/day).

Soil profiles established in May, July and September showed different behavior depending on the watering conditions and the climatic demand. For measurements made at 1.4 m from trunk (G_1), soil water content values ranged

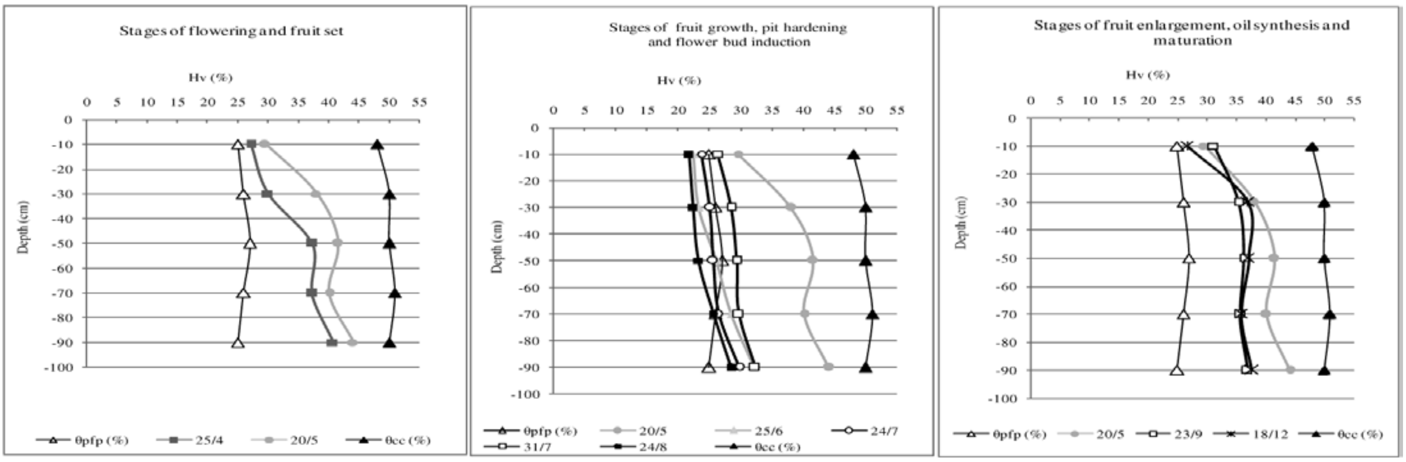

Fig. 9 - Soil water content curves observed at different stages of fruit development.

between 30 and 42% (Fig. 10), providing distinguishable profiles with constant differences between the lowest and the highest values within each trench of soil. However, minimum and maximum soil water contents were not observed during the driest (S) and the wettest period (P), respectively. Minimum values of H_v were recorded in the first 40 cm in May (S) and at deeper depths (0.40-1.20 m) in July (I), while maximum values were recorded in July in the superficial top layer, in September for the 0.20-0.60 m layer and in May at deeper depths (0.60-1.20 m).

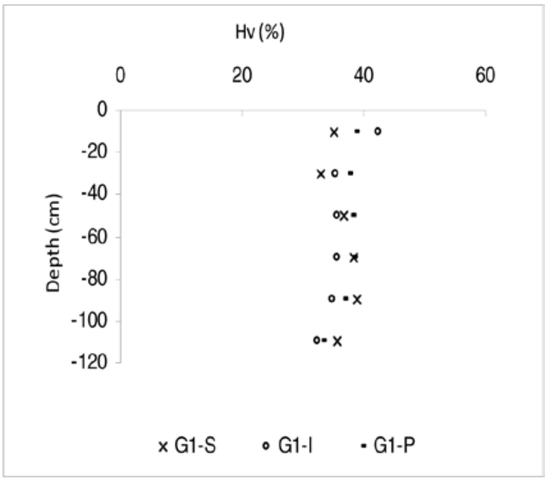

Fig. 10 - Soil water content (H_v, %) measured within the first reservoir (G_1). Measurements were made to 1.2 m depth at a distance of 1.4 m from trunks on May (29-05-2003) after a 20-day period of dryness (G_1-S), in July (16-07-2003) during an irrigation period (G_1- I) and in September (23-09-03) following the first heavy autumn rains (G1-P).

Groups G_2, G_3 and G_4 showed important variations between H_v values within the top soil layers (0-0.40 m) and small differences at deeper depths despite their distances from trunks (2.0 m, 2.8 m and 4.2 m) (Fig. 11). Minimum values (20%) were recorded in May and July despite the different climatic conditions, while the highest values of soil water content were about 40 % at all depths.

4. Discussion and Conclusions

This case study demonstrates the potential of using the neutron probe, TDR and gravimetric measurements to determine soil water content in a young olive orchard, taking into account the heterogeneous distribution of roots, localized irrigation and low canopy shade. Values of H_v were obtained by using the probe calibration curves established specifically for the SOLO 25 apparatus for each trench of soil. These curves cannot be used in any other situation.

Data collected with the different methods and apparatus showed positive correlations between soil water content measurements. This result is of practical interest because it indicates that any of these apparatus or methods can be used depending only on their availability. For example, the relationship developed between the two types of access tubes allowed us to use with confidence the PVC-polyamide tubes which were assembled locally with a lower cost. Regarding the apparatus, the TDR with probes installed vertically has proven to be fast, accurate and non-destructive, but it allowed measurements in one location only. This is a major disadvantage. On the contrary, gravimetric measurements can be made at any location and the method is suitable for calibrating other methods, although it is destructive and hard to carry out. Measurements made with the neutron probe are difficult. The apparatus requires specific calibration and some care should be taken when using such radioactive probes. With regard to these ‘constraints’, uncertainties arise because soil water content monitoring is incomplete as it is impossible to do measurements at all depths and in all directions. For the neutron probe, it is important to know if the observed variance of water content measurements is really due to errors associated with the location, which can be randomly distributed or spatially structured, or to errors arising from the use of a neutron probe itself. Indeed, uncertainty intervals are also influenced by the charge of the probe battery, the number of access tubes used, their placement and the depths at which they were installed. The number of access tubes should be determined depending on the heterogeneity of the or-

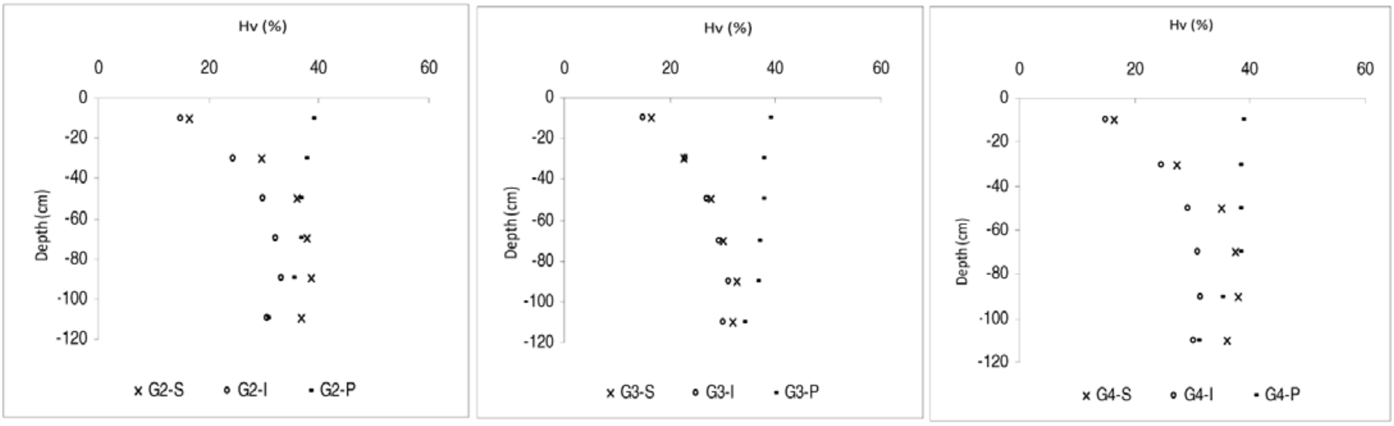

Fig. 11 - Soil water content (%) measured within the second (G_2), third (G_3) and fourth (G_3) reservoirs. Measurements were made to 1.2 m depth at distances of 2.0, 2.8 and 4.2 m from trunks, respectively, in May (29-05-2003) after a 20-day-long period of dryness (G_1-S), in July (16-07-2003) during an irrigation period (G_1-I) and in September (23-09-2003) following the first heavy autumn rains (G_1-P).

chard in order to avoid situations where sample data size is not sufficiently distributed in the field. About 25 locations would be necessary to obtain a mean value with a relatively high precision; observations are thus considered independent of one another regardless of their location in the field. It is also obvious that when installing soil-water measuring devices in the plant row in the irrigated field, at least one device should be located in each of the major soil types to take into account all soil occupation cases. Additional care should be taken with regard to possible drift in the electronic device: (1) counting in a water medium before and after profiles are sampled, (2) using the apparatus with a fully charged battery and (3) the use of a specific d_a value for each trench of soil rather than an average value for all soil layers when the soil texture is variable. However in light of recent concepts introduced in soil physics studies, and as previously stated, it is obvious that the auto-correlation between measurements in estimating the variance of the mean must be taken into account.

Soil water contents varied consistently according to the proximity of measurements to trunk and depth. Maximum variations were observed in the first top soil layers at 0.40 m from trunks as a result of the heterogeneous distribution of roots. There was a massive presence of roots near the trunk, mainly confined to the canopy projected area (Masmoudi *et al*., 2007; Masmoudi-Charfi *et al*., 2011). These results are concordant with those reported by Bonachela *et al*., (1999), Fernandez and Moreno (1999), Palese *et al*., (2000), Fernandez *et al*., (2003) and Connor and Fereres (2005) regarding high root densities in these areas. Some roots were also found at greater distances from the trunk, outside the canopies, i.e. within the reservoirs G_2 and G_3 but with lower densities in comparison to values obtained within the first compartment. This indicates that root uptakes are still possible in these areas, and these roots may have a significant role in enhancing root absorption and water transfer. Furthermore, results showed that the zones where roots develop behave differently, even below the canopy, involving different processes of water uptake and depletion. Unfortunately it was not possible to separate these processes in the present study to determine if these roots are more active than those located near the trunk or not. Fernandez and Moreno (1999) and Connor and Fereres (2005) explain that root densities are necessarily higher in the area of irrigation but roots may be less active. On the contrary, roots far from the trunk may be larger with numerous fine roots and thus they are more active. In another study carried out during the same year, Abid-Karray (2006) reported the presence of lateral water transfers within an olive orchard cultivated in central Tunisia under complementary irrigation. High water depletion was observed in that olive orchard and others cultivated under semi-arid and arid climates due to advective transfers of heat in soil (Fernandez *et al*., 1990; Fernandez *et al*., 1991; Villagra *et al*., 1995; Bonachela *et al*., 1999; Granier *et al*., 2000; Fernandez *et al*., 2003). This makes the situation more complex because roots situated outside of the projected canopy limit may contribute significantly to supply other reservoirs. Their role is however, highly dependent on the distance from the point of water but also the stage of development. We have published in previous papers (Masmoudi-Charfi and Ben Mechlia, 2007 and 2008) that under irrigated conditions young olive trees cultivated in this same location continued to grow even during the winter months, under different watering conditions (extreme rainy and rainless years), however with relatively low rates. Variability of soil water content is also dependent on soil coverage, which varied consistently from year to year, following the season, the severity of pruning and measurement site, thus modifying significantly the relative importance of the evaporative processes involved within each soil reservoir (Dichio *et al*., 2002; Masmoudi *et al*., 2004; 2007). This is because the contribution of the different processes of water uptake and water depletion depend on the amount of solar radiation intercepted by the tree canopy, which is the most important factor controlling water losses and extension of the leaf area. Water applied during the growing season seemed to be sufficient to meet the overall tree water needs although some water shortage was observed during the fruit set-maturation period. Stocks of water recorded at the beginning of the growing season (in May) were apparently insufficient to insure suitable growth of the tree, but high enough to assure early fruit growth. However, the lack of water observed from mid- July to end of August under high evaporative demand, reduced both tree height and fruit size (-10%), fruit weight (-26%) and also fruit number through an important fruit drop observed early September. Comparative results between the year of study and the preceding year showed a significant reduction of yield at harvest. Six-year-old olive trees yielded 1.9 T/ha (2003 was normally an ‘on’ year), while yield exceeded 2.0 T/ha in 2002 (‘off’ year). These different responses may be inheritent to other exogenous factors like soil type, pruning, and fertilizer schedules (Masmoudi-Charfi and Ben Mechlia, 2009) or to some endogenous parameiters which have an impact on how irrigation changes affect the production and growth levels. In September, although water was abundant and trees were loaded with fruits, water uptakes seem to be reduced due to the decrease of climatic demand. These results are supported by observations of sap fluxes recorded during the same period (Masmoudi-Charfi *et al*., 2011; 2013), showing that when water is available, sap flux measurements increased in correlation with the increasing climatic demand.

This experiment, concerning the choice of devices used to measure soil water content, despite the observed constraints, has practical interest. The positive correlations developed between soil water content measurements made with the different methods and apparatus indicate that any of these devices can be used indifferently, depending only on their availability and ease. Particularly, the relationship developed between the two types of access tubes allowed us to use with confidence the PVC-polyamide tubes assembled locally with a lower cost. This study has shown also that soil water content consistently affects tree height and fruit growth rates and varies depending on the depth and distance from the trunk. This spatio-temporal variability makes it difficult to provide proper assessment of the components of the water balance, if it is used for water consumption estimation in young orchards. Therefore, associating methods should be used that make it possible to distinguish between soil evaporation and water lost by transpiration like sap flux measurements. Additional measurements of root activity are also necessary to confine intervals in simulated uptake distributions. Nevertheless, these methods and estimations remain useful tools to decide when and how to irrigate, how much water is stored in the soil for plant use (soil water logging capacity) and to determine allowable water depletion.

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