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Root distribution in young Chétoui olive trees (*Olea europaea* L.) and agronomic applications

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Key words: irrigation, overall root length, root-canopy ratio, root density, root volume, water requirement.

Abbreviations: ETc (mm)= Crop evapotranspiration as determined by the FAO method (Allen *et al*., 1998).
ET* (m^3)= Evapotranspiration volume of an individual tree relative to its root area.
K_c =Crop coefficient.
K_r = Minorative coefficient introduced in the formulae of ET_c - FAO to take into account the soil coverage.
K_{supply} = A supply ratio determined in order to link the water supplied to trees to the evaporative demand, it takes into account only the tree-related quantities.
ET_o (mm)= Reference evapotranspiration determined following to Penman-Monteith equation.
P_e (mm)= Effective rainfall determined following the USDA-SCS method (FAO, 1976).
I (mm)= Irrigation amount supplied during the irrigation period.
I*(m^3)= Irrigation amount supplied by localized system or in small basins around the trunk.
P (mm)= Total rainfall.
P* (m^3)= Effective rainfall for a single tree received around the trunk.
Sc (m^2)= The maximum projected canopy area determined for each of the six trees assuming a circular shape.
Sr (m^2) = Area concerned by tree transpiration i.e. where roots are active.
(t)= The number of years from planting.
Lo, Lx= Dimension of interest respectively at planting and at maximum growth.
α, β = Adjustment parameters within the logistic root and canopy growth curve.

Abstract: **The study was carried out to have a comprehensive view of the root system behavior of young olive trees cultivated under field conditions. The experiment involved irrigated trees (*Olea europaea* L., cv., Chétoui) cultivated at 6x6 m^2 spacing in Mornag (36.5°N, 10.2°E), northern Tunisia. The way in which roots explore the soil volume during the first years after planting was explored through 'in situ' root system drawings and estimation of root densities. The relationship between canopy and root growth parameters was also investigated. The last section of this paper proposes a methodological approach for determining irrigation requirements of young olive trees and how water supply could be linked to the development of canopy and root system during the first years of cultivation when ground cover and the root system are not completely developed. Some agronomic applications were then deduced concerning water and fertilizers for such orchards. Results show that the main development of the olive root system occurs during the two to four first years of cultivation confining most roots (70%) to the top soil layers (20-40 cm). Maximum root densities were observed at this depth at a distance of 0.4 m from trunks. For young trees, water and fertilizers should be supplied at these depths and distances from trunk to allow easy and efficient root absorption. Obtained results also show a significant relationship between canopy and root areas which can be approximated by a linear model (r = 0.94). The root-canopy ratio estimated from their areas decreased rapidly beginning from the second year after planting, resulting from the establishment of competition between vegetative growth and fruiting. The optimum ratio root length/leaf canopy area of 2.3 km m^{-2} was found for the six-year-old tree indicating good equilibrium between the above and underground parts. The mathematical model developed on the basis of canopy cover and root extension allows precise estimation of water needs taking into account the actual root surface. However, while the canopy cover measurement was relatively easy to carry out, it was much more difficult to determine the surface covered by the root system. Results obtained in the present work also show an over-estimation of water needs when the FAO method is adopted to estimate the evapotranspiration of young trees.**

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1. Introduction

The primary function of the root system, i.e. water absorption and acquisition of soil nutrients, has a great influence on many of the physiological processes in the tree (Doussan *et al.*, 2003). However, despite of this importance, the root system is possibly the least explored area in crop physiology because of the difficulty involved in reaching it, in addition to the highly spatial-temporal variability which can generate many constraints to root extension. Amongst the first papers dealing with this area, are those of Yankovictch and Berthelot (1947), Vernet and Mousset (1963) and Abd-El-Rahman *et al.* (1966) which were carried out in North Africa, mainly on cultivars Chemlali and Picholine Marocaine. Research conducted a few years later in Spain and Italy investigated the relationship between water and root extension (Pisanu and Corrias, 1971; Bohm, 1979; Nunuez-Aguilar *et al.*, 1980; Martin-Aranda *et al.*, 1982; Michelakis and Vougioucalou 1988; Pastor *et al.*, 1998; Smit *et al.*, 1999; Palease *et al.*, 2000). It was shown that apart from genetics and the origin of the plant (Ayachi-Mezghani, 2009) root distribution and extension can be markedly influenced by neighboring trees and soil texture and depth (Ben Rouina *et al.*, 1996). Also, roots proliferate within the potential root zone regardless of irrigation application and method (Fernandez *et al.*, 1991, 1992, 2003; Fernandez and Moreno, 1999; Connor and Fereres, 2005). These last authors noted that localized irrigation increased root length density of Manzanilla olive trees but it decreased their spread, largely confining them within the wetted volume and nearby trunks. They reported also that except under the canopy, roots were less frequent in the top layers than in deeper strata.

Root extension is also dependent on the available carbohydrate resources (Dichio *et al.*, 2002) and growth stage (Michelakis, 2000). Rapid growth is observed in spring and autumn; it depends on water supply. Root growth precedes shoot growth and may be drastically limited by the previous year's fruit load. In fact, when no competition for carbohydrates occurred with other organs, for example for young olive trees or/and for vigorous canopy growth trees, important root extension and greater root densities were reported (Palease *et al.*, 2000). In contrast, limited carbohydrate resources led plants to reduce their canopy growth and root length and even could deteriorate the root-canopy ratio as a result of competition between shoots, flowers, fruits and roots (Dichio *et al.*, 2002). This relationship between root growth and the above-ground development is complex because it integrates many other factors and physiological processes like temperature, radiation, hormones, variety and alternate bearing.

Reduction of the root-canopy ratio implies systematic reduction of the capacity of the rooting system to absorb water. In terms of root balance, the importance of the water collecting system resides in its capacity to obtain water to support the transpiring leaf area (Connor and Fereres, 2005; Connor, 2006) and it can be determined via an estimation of total root length through monitoring of root density. These techniques are reported by Tennant (1975) and Fernandez and Moreno (1999). Such measurements could provide reliable estimates of comparative activities. For olive trees, Connor and Fereres (2005) reported root densities ranging between 0.1 and 1.0 cm cm^{-3}. These values are lower than those provided for herbaceous crops and some deciduous orchards, although olive root systems can be extensive and deep.

It appears from this short review that fundamental research on this subject is of prime interest: when and where the roots grow is crucial to understanding the functioning of the root system and its relationship with the above-ground organs. In fact, without precise information on root distribution, we cannot expect to efficiently manage the irrigation of the orchard. For these purposes, we have carried out the present study in order to have a comprehensive view of the root system behavior of young olive trees cultivated under field conditions.

In this work, we examine how roots explore the soil volume during the first years after plantation. The relationship between root and canopy development was also investigated. The last section of this paper proposes a methodological approach to determine irrigation requirements of young olive trees and considers how water supply could be linked to the development of canopy and root system during the first years of cultivation when ground cover and the root system are not yet completely developed.

2. Materials and Methods

Olive orchard

The study was carried out during the period 1998-2003 at the experimental farm of the Institut National Agronomique de Tunisie, located 15 km south of the capital Tunis (36.5ºN, 10.2ºE), northern Tunisia. In this region, climate is Mediterranean with yearly averages of 450 mm rainfall and 1200 mm reference evapotranspiration. It is dry and hot from May to September. The orchard, of 1.6 ha, was planted in 1998 at 6x6 m^2 spacing on a textural clay soil (29%C, 49%L, 23%S) of about 2 m depth. The volumetric soil water content was measured in the laboratory at field capacity (50%) and at the wilting point (26%). Crop management practices carried out in the orchard, i.e. pruning, fertilizer (Masmoudi-Charfi and Ben Mechlia, 2009) and pest management practices, were similar to those applied in intensive orchards (Masmoudi-Charfi, 2006; Masmoudi-Charfi *et al.*, 2006). The trial concerned trees of cultivar Chétoui, which is the main oil variety of northern Tunisia.

Climatic data and irrigation management

Daily crop evapotranspiration (ET_c) was determined according to Allen *et al*. (1998) for the non-standard conditions such as: $ET_c = ET_o \times K_c \times K_r$, K_c ranging between 0.3 and 0.5 according to age, while K_r values were determined experimentally and varied between 0.69 and 0.75. For this purpose, a large white grilled (10 cm/10 cm) sheet was used. It was placed below the tree and the shade squares were counted and compared to the total number of squares (those lighted by sun and those shaded by leaves). This percentage represents the K_r value. Daily reference evapotranspiration (ET_o) was computed according to the Penman-Monteith equation, with maximum and minimum yearly values of 1320 mm (1999) and 1212 mm (2003), respectively. Data relative to rainfall, ET_o and temperature are reported in Table 1. All climatic data were recorded continuously with an automatic weather station located about 150 m from the young olive orchard.

During the six years of the study, rainfall amounts varied from 327 mm (2001) to 790 mm (2003), while effective rainfall amounts ranged between 226 mm and 546 mm. These values were determined according to the USDA-SCS method (FAO, 1976).

Accounting for these conditions, olive trees were irrigated every year during the spring-summer season. Water flows were programmed four times per season regardless of the critical stages and water availability. Irrigation was supplied by furrows (basin and drain) during the four first years and then by a drip system (2002 and 2003). Two parallel drip lines were fixed on the soil surface at about 0.5 m from trunks. There were four emitters per tree, two at each side of the tree trunk, separated 1 m from each other; each having a 4-L h^{-1} flow rate. The area wetted by irrigation application varied between 1 m^2 (1st year) and 6 m^2 (6th year). Watering conditions for the whole period are given in Table 2.

Water requirements were covered at levels varying between 0.3 ET_c and 1.1 ET_c according to year and water availability.

Measurements

Soil water content. The volumetric water content of the soil was measured with a neutron probe (SOLO 25) which was previously calibrated for the soil in question (Masmoudi-Charfi, 2008). Twenty-eight access tubes, 1.5 m long, were placed at the corners of a square of 2 m^2 below the canopy but also within the tree line and between tree lines. The soil moisture in each of these tubes was recorded frequently during the irrigation period every 0.3 m to 1.2 m depth, and the mean calculated separately for each position: below the canopy, far from the emitters, along and between the lines of tree (unpublished data). For the top 0.2 m soil layer, soil water content was determined by gravimetry. More details are given in Masmoudi-Charfi (2008).

Table 1 - Climatic data recorded during experimentation (1998-2003)

	1998	1999	2000	2001	2002	2003
Annual rainfall (mm)	376	440	410	327	345	790
Effective annual rainfall (mm)	260	304	283	226	238	546
Absolute T_{max} (°C)	47.0	41.0	44.0	42.0	43.0	46.0
Absolute T_{min} (°C)	3.0	1.0	4.0	3.0	3.0	3.0
Average T_{max} (°C)	25.0	23.7	25.2	25.8	25.6	24.9
Average T_{min} (°C)	13.3	15.0	14.8	15.8	15.5	14.9
Annual ET_o (mm)	1313	1320	1293	1282	1231	1212

Table 2 - Water requirement and irrigation application for young olive trees of cultivar Chétoui during the experimental period

	1998	1999	2000	2001	2002	2003
Irrigation system	Basin	Basin	Drain	Drain	Drip	Drip
First irrigation	March	May	April	April	March	May
Last irrigation	August	September	September	September	August	September
Dose (m^3/tree)	0.12	0.18	0.22	0.44	0.7-1.7	0.3-1.0
Irrigation amount (m^3/tree/year)	0.84	0.72	0.88	1.76	4.98	5.41
I + P_e (mm)*	140	61	180	141	248	389
ET_c (mm)*	243	241	291	287	273	368
I+P_e / ET_c	0.6	0.3	0.6	0.5	0.9	1.1

(*) indicates that values are determined for the irrigation period.

P_e is the effective rainfall determined according to the USDA-SCS method (FAO, 1976) and I is the irrigation amount.

The ratio I+P_e / ET_c was calculated for the irrigation period.

The tree downward projection canopy flat area varied between 2% (first year) and 33% (sixth year).

Root distribution. Distribution of the root system was studied during the rest period (November-December) on the same Chétoui olive trees by extensive observations of their root system. The trench method was used as described by Fernandez *et al*. (1991). For this purpose, a large pit was opened at 0.4 m from the trunks and roots were counted on the internal trench wall, which was divided into five layers of 0.2 m width each and down to 1.0 - 1.2 m depth. Root diameter was measured by means of a caliper 1/100. Maximum distance of roots from trunk was determined at each soil layer in order to estimate lateral root extension. Total volume of soil and the area explored by the root system were determined assuming central symmetry to the trunk.

Root density. Root densities were determined on the same Chétoui olive trees by using the cylinder method as described by Fernandez *et al*. (1991). Soil samples were taken during the rest period by a conventional auger at 0.4 m, 0.8 m and 1.2 m from trunks in order to quantitatively assess the importance of the root system through an estimation of root densities as described by Tennant (1975). Samples were taken within layers of 0.2 m width, down to 1.0 - 1.2 m depth, following east and south directions, along the line of drippers (south) as well as perpendicular to this. They were then washed out abundantly and sieved through a 0.5 mm screen. Extracted roots were counted by adopting a reference scale (Tennant, 1975). Root length was then derived from the average root density value for each of the six trees. Figure 1 presents details on both protocols. With this scheme, it was possible to obtain information on root distribution in the zones affected and not affected by irrigation.

Canopy measurements. Canopy diameter measurements were monitored at the same time as the study of the root system and on the same experimented trees. The maximum projected canopy area (S_c) was determined for each of the six trees assuming a circular shape. These measurements were used to set a typical model of growth and to examine the relationship between root and canopy development.

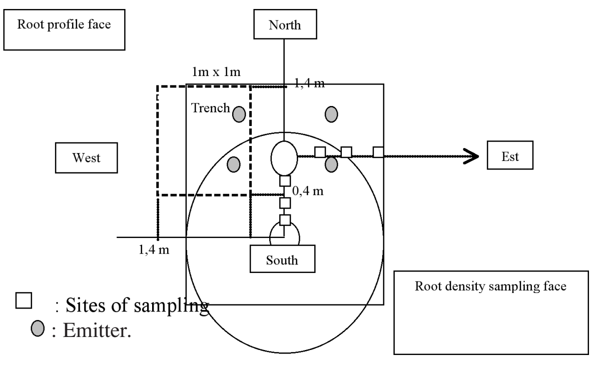

Fig. 1 - Scheme of sampling to determine root distribution and root densities for young olive trees aged one to six years. Root profiles were mode following to NW direction while samples of root density determination were taken at 0.4 m, 0.8 m and 1.2 m from trunks to 1.2 depth following to SE direction.

Canopy leaf area was determined for the six-year-old olive tree by computing the number of leaves on representative shoots and estimating its specific leaf area. It reached 14 m^2 on May 2003. This value was adopted to calculate the root length/leaf canopy ratio.

Methodological approach to determine irrigation requirements of young olive trees. This section proposes a methodological approach to determine irrigation requirements of young olive trees and how the water supply can be linked to the development of the canopy and root system during the first years of cultivation when ground cover and root system are incompletely developed. Determination of water requirements according to the FAO method (Allen *et al*., 1998) is adequate for standard conditions, i.e. when soil coverage reaches 60% or more. However, when the coverage area is less, a reductive coefficient K_r is introduced (COI, 1997; Allen *et al*., 1998). In some cases, particularly for young and new orchards (low tree canopy cover), this coefficient may not be precise enough to allow good estimation of water needs. In addition to problems estimating K_r values, the K_c is strongly affected by conditions that influence evaporation from the soil surface (Orgaz *et al*., 2006). Recently, Testi *et al*. (2004) proposed a simple linear relationship between the olive ground cover (and Leaf Area Index) and the average K_c of the summer months, valid for ground cover fractions up to 0.25, along with its variation when wet surface soil spots are present. These authors indicate that this relationship does not apply outside a rainless summer, and the contribution to soil evaporation from the drip system depends on the surface area and location of the wet spots and is not scalable.

Thus, we developed the following approach which is designed to determine the consumptive use of olive trees in relation to their canopy growth and root development during the first six years after planting.

Before full development of the root system, only a fraction of rainfall water is accessible to trees. Thus, the water balance equation should consider the area concerned by tree transpiration *i.e*. where roots are active (S_r); S_r is assumed to be circular and to increase following a logistic-shaped curve.

Root extension, as well as canopy increase, seems to coincide with a logistic growth curve as given by the following equation:

$$L(t)=Lo+\frac{Lx-Lo}{1+\exp[\alpha(t-\beta)]}$$

where (t) is the number of years from planting; Lo, Lx dimensions of interest, respectively, at planting and at maximum growth; α, β are adjustment parameters.

In order to link the water supplied to trees to the evaporative demand, a supply ratio (K_{supply}) that takes into account only the tree-related quantities is defined by this equation:

$$K_{supply} = (P^* + I^*) / ET^*$$

Considering that irrigation (I*, m^3) is supplied by a localized system or in small basins around the trunk, only a small surface is wetted and affected by soil evaporation and transpiration. Irrigation water is therefore assumed to be fully accessible to the root system of the tree. On the other hand, effective rainfall for a single tree (P*) is taken as the volume of rainfall water available to the root system which could be approximated by the following equation:

$$P^* (m^3) = P (m) \times S_r (m^2)$$

P is rainfall, considered here as total rainfall.

The evapotranspiration volume of an individual tree (ET*) can be estimated from the root area of the tree as:

$$ET^* (m^3) = K_c \times ET_o (m) \times S_r (m^2).$$

Different water supply ratios are determined as K_c - FAO, I/ET_o, P*+I*/ET*and I*/ET*. The ratio I/ET_o is the irrigation supply, P*+I*/ET* is the volumetric total supply and I*/ET* is the volumetric irrigation supply. These ratios are for the period April-August over the first six years of olive tree cultivation. Values are represented in the same figure to compare results.

3. Results

Soil water status

Simultaneous monitoring of soil moisture carried out during the 2003 campaign at the canopy limit and near the emitters showed that soil water contents vary from 15 to 39% according to depth and distance to trunk (Fig. 2). Low values of soil water content were observed in the upper layers, while minimums were recorded within the superficial strata (0-20 cm) as a result of soil water evaporation and root absorption. This result confirms the concordance between root development and soil water depletion. The results showed large variation between measurements at the limit of the canopy, while low variation of soil moisture was observed near the emitters with values ranging between 32 and 38% according to depth (Fig. 2).

Root system drawings

Root profiles for the tagged trees show two or three types of roots according to age (Fig. 3). During the first years after planting, trees developed fine roots in the upper 0.2 m of the soil layer, which then extended rapidly in lateral and vertical directions with inclinations varying from 30° to 60° depending on their size and position. For older plants, larger roots were observed beyond the first 0.3 m and they developed horizontally with numerous fine roots.

The number and diameter of roots which emerged from the lateral face of the trench are summarized in Table 3.

Results indicate that most roots (70%) are localized in the first 0.6 m of soil. The maximum number is found in the top layers, with diameters ranging between 2 mm (one-year-old tree) and 32 mm (four-year-old tree). Some roots developed in deeper strata, reaching 1.0 m depth. Very few roots were found below this depth even for the oldest tree.

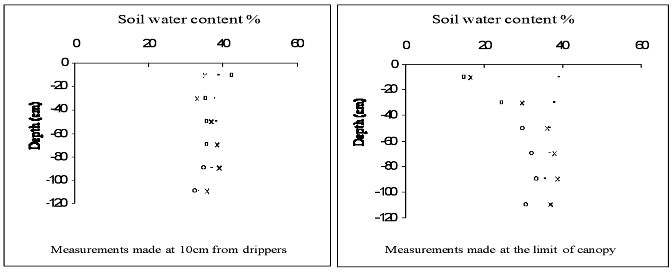

Fig. 2 - Soil water content (%) measured at two sites: on the left at 10 cm from the emitters and on the right at the limit of the canopy during the 2003 campaign.

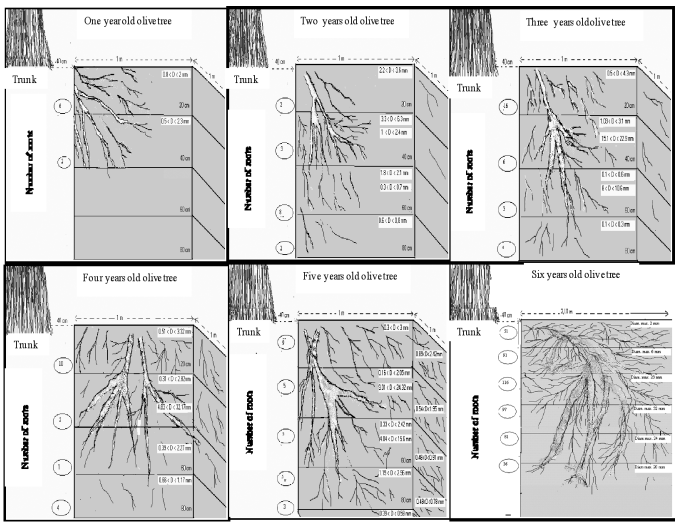

Fig. 3 - Drawings of the root system of young olive trees of cultivar Chétoui aged one to six years. Roots were counted on the internal trench wall, down to 1.0 - 1.2 m depth depending on age.

Table 3 - Maximum number of roots and root diameter emerging from the trench face for each soil layer for olive trees aged one to six years

	Age (year)					
Soil layer (cm)	1	2	3	4	5	6
0-20	6	2	16	10	9	51
20-40	2	3	6	5	5	91
40-60	0	8	3	1	3	116
60-80	0	2	4	4	5	97
80-100	0	0	0	0	3	81
Total number of roots	8	15	29	20	25	472
Maximum root diameter (mm)	2	6	23	32	24	27

Extension of the root system

Results presented in Table 4 show that the main development of the root system occurred during the first two to four years of cultivation, horizontally and within the top layers (0.2-0.3m). During this period, the soil volume explored by roots increased at a regular rate of about 1.0 m^3 yearly. For the three-year-old tree, roots explored a volume of 3.65 m^3. The soil volume explored by the root system of the five-year-old-tree represents 47% of that reached by the older tree (six-year-old tree).

Root density

Results relative to root density estimation are reported in figure 4. A noticeable root concentration is observed for both east and south directions and close to trunk in the top layers around each of the six trees. Average values varied between 0.001 cm cm^{-3} and 0.670 cm cm^{-3} depending on depth, distance to trunk, direction and tree age.

Greater values, by up to 0.5 cm cm^{-3}, were recorded in the first 60 cm and at 0.4 m from trunk. These values decreased significantly as the distance to trunk increased (except some measurements for two- and three-year-old plants). Roots were less frequent at all depths outside the canopy limit and particularly for the deeper layers. At these depths, however, it should be mentioned that root densities rarely exceed 0.4 cm cm^{-3} for both directions, while average values ranged between 0.067 cm cm^{-3} and 0.303 cm cm^{-3} (Table 5).

Root system length

The overall length of the root system varied from 1.0 km to 33.9 km depending on age (Table 6).

A significant increase of the overall length of the root system was observed for the six-year-old tree. It was 4.8 times greater than that recorded the previous year. The lowest value was recorded for the four-year-old tree. There was no apparent cause which could explain this result.

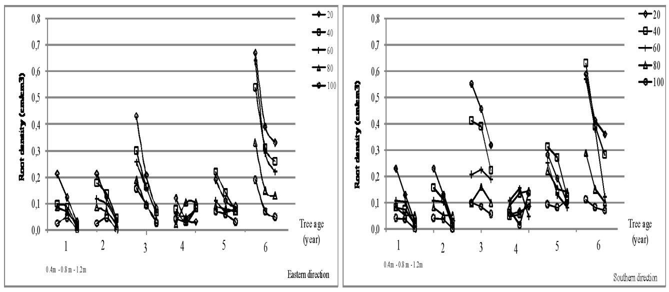

Fig. 4 - Root densities (cm cm^{-3}) recorded for olive trees of cultivar Chétoui aged one to six years based on direction and depth. For each tree, three measurements were carried out for both directions at different distances from trunk; the first observation was made at 0.4 m, the second at 0.8 m and the third at 1.2 m.

Root development and canopy growth

Results presented in figure 5 showed for tree aged one to four years that roots grew at higher rates than

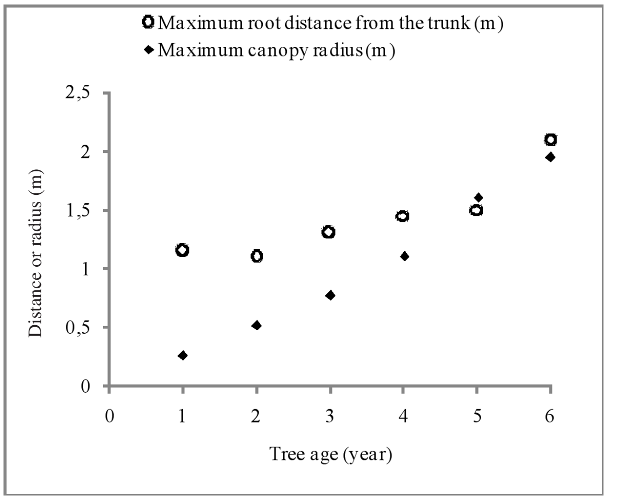

Fig. 5 - Maximum root distance from the trunk (m) and Maximum canopy radius (m) following to age for olive trees Chétoui ages one to six years.

Table 4 - Maximum distance of roots to trunk (m) and volume of soil explored by the root system (m^3) for olive trees aged one to six years

Depth (cm)	Age (year)					
	1	2	3	4	5	6
0-20	1.05	1.05	1.25	1.45	1.50	2.12
20-40	1.15	1.10	1.30	1.45	1.45	1.95
40-60	0	1.00	1.25	1.25	1.25	1.80
60-80	0	0.80	1.00	1.25	1.25	1.65
80-100	0	0	0	0	1.00	1.55
Explored soil volume (m^3)	1.45	2.55	3.65	4.60	5.30	11.2

Table 5 - Average root densities (D_r, cm cm^{-3}) determined for trees aged one to six years

	1	2	3	4	5	6
D_r (cm cm^{-3})	0.067	0.079	0.196	0.075	0.133	0.303

Table 6 - The overall length of root system (L_r, km) for trees aged one to six years

	1	2	3	4	5	6
L_r	1.005	1.975	7.056	3.450	7.049	33.936

canopy radius. Then, differences between the canopy radius and the root-to-trunk-distance decreased. Roots reached for the six-year-old tree a maximum distance to trunk of 2.10 m, while the canopy limit was observed at 1.95 m. The projected canopy area (S_c) increased slowly after planting to reach 0.21 m^2 for the one-year-old tree and 11.94 m^2 for the six-year-old-tree (Table 7), while the root area progressed at a constant rate of 1.2 m^2 per year to reach 13.8 m^2 for the six-year-old-tree.

A significant relationship was found between canopy (S_c, m^2) and root (S_r, m^2) areas, which can be approximated by a linear model with a correlation coefficient r of 0.94, as illustrated by Figure 6, where

$$S_c = 1.183\ S_r - 3.602 \qquad (R^2 = 0.876)$$

The S_r/S_c ratio derived from both canopy and root areas decreased significantly from 20 to 0.9 depending on tree age. For the four-, five- and six-year-old trees, this ratio approximated the unit.

A decrease of the S_r/S_c ratio implies a tendency to equilibrium between the under-ground and above-ground organs beginning from the fourth year after planting, which apparently results from the establishment of competition between shoots, roots and fruits (and explains the decrease of this ratio). In fact, trees began to produce olives within the second year after planting and the first commercial crop arrived in year four (6.5 kg / tree).

Results indicate also that plants seem to be able to adjust their root systems to the larger above-ground development during the winter rest. This feature is well represented by the root length/leaf canopy area ratio. A value of 2.3 km m^{-2} of leaves for the six-year-old tree was found in the present study, a value which is considered optimum for such conditions.

Irrigation supply as a function of canopy and root development

In order to link the water supplied to trees to the evaporative demand, a supply ratio (K_{supply}) that takes into account only the tree-related quantities is defined as developed in section 'Measurements. Methodological approach to determine irrigation requirements of young olive trees'. This ratio could be considered as a crop coefficient for young trees when reference evapotranspiration, rainfall and irrigation amounts are computed according to the previous equations and expressed in m^3/tree. Adoption of such a ratio allows estimation of irrigation requirements for different rainfall and evapotranspiration regimes. The different water supply ratios, K_c - FAO, I/ET_o, P*+I*/ET* and I*/ET*, determined for each of the six olive trees are given in Figure 7 for comparative purposes.

Results show that the ratio of applied irrigation (I, mm) to reference evapotranspiration (ET_o, mm) during the dry season from April to August was very low. It increased from 0.02 to 0.14 when trees grew from one to six years. When using the volume method to calculate the irrigation and precipitation falling on the area covered by roots, K_{supply} comes very close to the K_c-FAO. Estimation of effective precipitation remains however big challenge for using the proposed method.

Table 7 - Canopy and root area estimations (m^2) of olive trees aged one to six years

	1	2	3	4	5	6
Root area (S_r)	4.20	3.80	5.30	6.60	7.10	13.80
Canopy area (S_c)	0.21	0.82	1.86	3.79	8.04	11.94
S_r / S_c	20.00	4.60	2.80	1.70	0.90	1.20

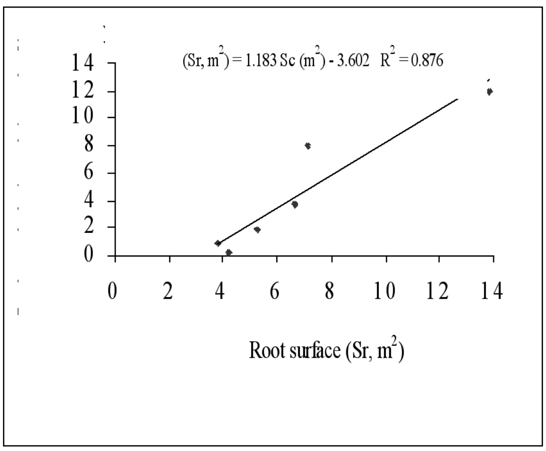

Fig. 6 - Relationship between canopy and root areas for young olive trees aged one to six years.

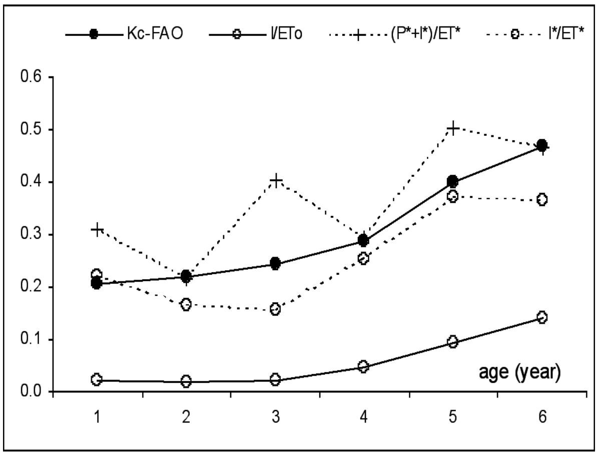

Fig. 7 - Variation of K_c-FAO, irrigation supply (I/ET_o), volumetric total supply (P*+I*/ET*) and volumetric irrigation supply (I*/ET*) ratios calculated for the period April-August over the first six years of olive tree cultivation, 1998-2003, Mornag - Tunisia.

4. Discussion and Conclusions

This study provides preliminary results on root distribution of young olive trees of cultivar Chétoui, which could be exploited to manage young olive orchards efficiently. Root profiles for trees aged one to six years show rapid extension of the root system during the first two to four years of cultivation following to horizontal direction. Most roots (70%) are localized in the first 0.6 m of soil with a maximum number developed in the top layers. Some roots developed in deeper strata, reaching 1.0 m depth, but at this age very few roots were found below this depth. The largest roots were observed beyond the first 0.3 m with maximum diameters between 2 mm and 32 mm according to age. Results indicate also that lateral fine roots are abundant and give rise to a fibrous root system which represents the main absorbing surface as it was reported by Palease *et al*. (2000). These roots originate from the branching of a parent root and constitute their ramifications, generally at right angles, as indicated by Doussan *et al*. (2003), who classified the roots into three main categories according to their ontogenesis: primary, adventitious and lateral. In our case, the primary root constitutes the main root of the cutting. It was not dominated at the outset by a principal axis as it occurs in trees grown from seedlings. Rather, many adventitious roots are produced from the base of the cutting. Similar results were found in the literature for young olive trees, although studies were carried out under different conditions. Abd-El-Rahman *et al*. (1966) reported for young trees, aged seven years and grown under 150 mm of rainfall, that roots are contained in the shallow tillage (0.15-0.30 m) to approximately 0.3 m from trunk. In Sardinia, Pisanu and Corrias (1971) observed a very shallow root system in the roots of excavated trees. Their photographs and drawings clearly illustrate the horizontal development of the roots and the fact that roots of contiguous trees avoid competition by developing outwards from the tree row. In Spain, Nunuez-Aguilar *et al*. (1980) observed for 12-year-old 'Manzanilla' olive trees, that most roots are localized in the outer layers at 0.45 m from the trunk with diameter less than 0.5 mm. Mickelakis and Vougioucalou (1988) observed for five-year-old 'Kalamon' olive trees cultivated in Create, a maximum number of roots at a depth of 0.4 m. Later, Bongi and Palliotti (1994) indicated that the root system of young olive trees is mainly confined to the top meter of soil, growing at depths between 0.15 and 0.40 m at a maximum distance of 0.30-0.40 m from the trunk.

Results relative to soil volume exploration showed a regular increase of about 1.0 m^3 yearly but this rate is apparently lower than that reported in other studies. For three-year-old trees cultivated on loamy soil in southern Italy, Dichio *et al*. (2002) found volumes of about 8.6 m^3 for the irrigated trees and 5.1 m^3 for those cultivated under rain-fed conditions (670 mm/year of rainfall). In our case and for trees of the same age, roots explored a volume of 3.65 m^3 only. This extension represents, according to Fernandez and Moreno (1999), Doussan *et al*. (2003), Fernandez *et al*. (2003) and Connor and Fereres (2005), the plants' evolutionary response to the spatio- temporal variability. It explains, in our case, the lateral spread of roots and the depths they achieve; soil characteristics (clay) and its mechanical resistance may adversely affected root exploration. Increases in soil strength during the summer months, as a consequence of occasional water shortage (interval between irrigations varying between 20 and 50 days), may have reduced the average number of laterals developed on the primary axes. During the following years (fifth and sixth years) the application of drip irrigation led trees to limit their root development, confining most roots to the upper layers with a noticeable root concentration observed for both east and south directions close to the trunk. An increase of root density is however observed with average values varying between 0.001 and 0.670 cm cm^{-3} depending on depth, distance to trunk, direction and tree age. Similar values ranging between 0.1 and 1.0 cm cm^{-3} were reported by Connor and Fereres (2005). Greater values of up to 0.5 cm cm^{-3} were recorded in the first 60 cm and at 0.4 m from the trunk. Values of root density then decreased, significantly as distance to trunk increased (except some measurements for two- and three-year-old trees). Roots were less frequent at all depths outside the canopy limit and particularly for the deeper layers. Nunez-Aguilar *et al*. (1980) observed similar results for 12-year-old 'Manzanilla' olive trees with highest values of about 0.7 cm cm^{-3} at 0.45 m from the trunk. For seven-year-old olive trees growing with only 150 mm mean annual rainfall, Abd-El-Rahman *et al*. (1966) also found maximum root densities in the top layers at 0.15 - 0.30 m and up to 0.3 m from the trunk. These results show good concordance between soil profiles made for the six experimental trees and their root density distribution, having agronomic applications, since they could be used to manage more efficiently irrigation and also fertilization. Water and fertilizer supplies should be given at these distances from trunks for young trees to guarantee their efficacy.

Many factors are cited to explain root density distribution (Fernandez and Moreno, 1999) amongst the cultural practices are reported in most papers. In our case, the six-year-old tree provided the highest values with average density of 0.303 cm cm^{-3}, however the root densities recorded for the three-year-old plant were greater than those observed for the older trees. Genetic factors inherent to the potentialities of that tree may be involved (Michelakis and Vougioucalou, 1988). However, it seems that the most influential factor that affected root density is the heterogeneous distribution of water in the orchard. Results showed spatial variability of soil moisture with lower differences between measurements near the emitters (values ranging between 32 and 38% depending on depth) and larger variation between measurements at the limit of the canopy. This result was unexpected, but it may indicate lower rates of root absorption around the emitter despite the high densities observed at this distance from trunk (0.4 m). For such a situation, Fernandez and Moreno (1999) indicated that sites of maximum root density may coincide with low root activity as a compensation mechanism; thus root activity may be higher in zones of low root density than in zones of high density.

The influence of soil water content on root distribution is reported by Fernandez *et al.* (1991), who observed that adequate watering makes roots continue to grow during the dry season, thus, increasing the period of their activity and preventing their shrinking during this period. Palease *et al.* (2000) and Bongi and Palliotti, (1994) indicated that root extension depends largely on the distributed water amounts and the irrigation frequency. Larger volumes of water would favor the existence of wider wet bulbs and could increase root length density. In opposite, low water availability can slow down root growth because roots are able to sense the soil dryness and order stomata to close; thereby reducing water losses and preventing excessive water stress. Water shortage may also increase mortality of fine roots even in the irrigated orchards; roots developed outside the wetted area during the rainy period may die.

Root distribution and densities are also highly dependent on leaf area and canopy development. In fact, this trial shows that olive tree establishes equilibrium between root and canopy development rapidly, around the fourth year after planting despite the larger extension of roots observed during the first two years in comparison to canopy growth. Such increases in root area could be explained as a need to adequate the root system to a more vigorous canopy development. Inversely, greater leaf area could provide greater total carbohydrates reserve for root activity. This relationship between leaf and root is very important to consider because dry soil conditions determine a cumulative effect over the years which indirectly affected root activity through an integrated chemical and hydraulic signaling mechanism controlling leaf water relationships, as stated by Fernandez and Moreno (1999). It could be represented by the under-/above-ground ratio. Our results show high values of this ratio during the first year after planting, indicating a greater availability of water per unit of leaf area. However, beginning from the second year after planting this ratio decreased rapidly to attain a minimum value of 0.9. Dichio *et al.* (2002) explains that a decrease of root-canopy ratio is a consequence of lack of water during the growing phase, which led plants to several physiological modifications; thus it can be used as an indicator of tree adaptation to water shortage.

Other reasons could be evoked to explain the decrease of this ratio such as the establishment of competition for nutrients between shoots, roots and fruits, which are considered the strongest sinks. The establishment of such competition is important to insure a balanced development of the tree, once it begins to set fruits. During this period of youth and first-fruit-set, the tree re-orientates the mobilization of carbohydrates (Proietti and Tombesi, 1996; Palease *et al.*, 2002) and high amounts of assimilates are drain to growing olives against the competing demand of the growing roots and shoots. As a results, the number of roots and their length could be reduced because their growth remain highly dependent of the available assimilates.

Under adequate watering conditions, olive trees seem to be able to adjust their root systems to the larger above-ground development during the winter rest essentially when no (or low) competition with other organs occurs. Such result was reported by Palease *et al.* (2002) and Connor and Fereres (2005) who indicate that this feature is well represented by the root length /leaf canopy area ratio. In our experiment we found a value of 2.3 km m^{-2} of leaves for the six-year-old tree. This ratio is concordant with the optimum values of 2.2 - 2.9 km m^{-2} which were determined for intensive plantations (Connor and Fereres, 2005), and this result is very important for the current work because it indicates that olive trees were adequately irrigated. Such management of water ensured good development of the root system and the canopy despite the difficulties involved in fixing the irrigation amounts for such young trees with regard to the incomplete soil coverage and root development.

For such young orchards, it is known that only a fraction of rainfall water is accessible to trees. Thus, the water balance equation should consider only the area concerned by tree transpiration *i.e.* where roots are active. This area is assumed to be circular and results show that it increases following a logistic-shaped curve (Masmoudi *et al.*, 2007). This factor was taken into account to develop a mathematical model which allows estimation of irrigation needs of young trees, based on the study of the root/canopy over a long period of time. In this model a supply ratio was determined as shown previously in order to link the water supplied to the evaporative demand that takes into account only the tree-related quantities. Results show that the ratio of applied irrigation to reference evapotranspiration during the dry season from April to August was very low. It increased from 0.02 to 0.14 when trees grew from one to six years. When using the volume method to calculate the irrigation and precipitation falling on the area covered by roots, the supply ratio comes very close to K_c-FAO. Estimation of effective precipitation remains, however, a big challenge for using the proposed method.

The present study provides preliminary results on root distribution of young olive trees of cultivar Chétoui, which could give insight into the efficient management of intensive orchards. However, these results should be enhanced by root activity observations. Furthermore, development of a more detailed study on young trees would be useful to get more information on the relationship between root activity and root distribution because sites of heavy root density may present lower root activity, even in young trees. In such study, the root system should be viewed as a population of roots with varying, although coordinated, morphological and physiological properties. Measurements of carbohydrate status at different stages of development at both root and canopy levels would also improve these results and give us more valuable information on the relationship between the rooting system distribution and canopy development, essential for irrigation requirement estimation as they determine evapotranspiration and water available for the root system. More knowledge is needed on root growth in young trees because they are more vulnerable to water shortages. For such trees, and particularly plants obtained from rooted cuttings, water uptake remains highly dependent on the effective areas of transpiration and water absorption. Thus, it is probably more convenient to consider evapotranspiration, rainfall and irrigation in terms of volume of water/tree instead of mm. Our progress in the future will be measured by our capacity to integrate knowledge on water supply, evaporative demand and the soil volume explored by the root system for different locations and planting densities.

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