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Root length density and soil water distribution in drip-irrigated olive orchards in Argentina under arid conditions

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Abstract. Several studies have evaluated many above-ground aspects of olive production, but essential root system characteristics have been little examined. The objective of our study was to evaluate root length density (RLD) and root distribution relative to soil water content in three commercial orchards (north-west Argentina). Depending on the orchard, the different drip emitter arrangements included either: (*1*) emitters spaced continuously at 1-m intervals along the drip line (CE-4; 4 emitters per tree); (*2*) 4 emitters per tree spaced at 1-m intervals, but with a space of 2 m between emitters of neighbouring trees (E-4); or (*3*) 2 emitters per tree with 4 m between emitters of neighbouring trees (E-2). All of the orchards included either var. *Manzanilla fina* or *Manzanilla reina* trees (5–8 years old) growing in sandy soils, although the specific characteristics of each orchard differed. Root length density values (2.5–3.5 cm/cm^3) in the upper soil depth (0–0.5 m) were fairly uniform along the drip line in the continuous emitter (CE-4) orchard. In contrast, roots were more concentrated in the E-4 and E-2 orchards, in some cases with maximum RLD values of up to 7 cm/cm^3. Approximately 70% of the root system was located in the upper 0.5 m of soil depth, and most of the roots were within 0.5 m of the drip line. For each of the three orchards, significant linear relationships between soil water content and RLD were detected based on 42 sampling positions that included various distances from the trunk and soil depths. Values of RLD averaged over the entire rooting zone and total tree root length per leaf area for the three orchards were estimated to range from 0.19 to 0.48 cm/cm^3 and from 1.8 to 3.5 km/m^2, respectively. These results should reduce the uncertainty associated with the magnitude of RLD values under drip irrigation as intensively managed olive orchards continue to expand in established and new growing regions.

Additional keywords: high density, *Olea europaea* L., root mass, soil auger.

Introduction

The expansion of modern olive production systems with high density plantings (i.e. >200 trees/ha) and intensive management techniques such as drip irrigation into established and new growing regions requires a greater understanding of many aspects of olive production (De la Rosa *et al*. 2007; Pastor *et al*. 2008). Above-ground phenomena such as shoot growth, reproductive development, and physiological leaf-level responses have been fairly well examined in olive, especially in response to water stress (e.g. Goldhamer *et al*. 1993; Fernández *et al*. 1997; Moriana *et al*. 2002; Gómez del Campo *et al*. 2008). However, relatively little information is available even at the descriptive level for olive root systems (Connor and Fereres 2005). As has been observed in other fruit trees, root system characteristics will likely become increasingly important as tree density increases due to limitations in soil volume that can be explored per tree and competition between trees for water and nutrients (Chalmers *et al*. 1981).

One of the most basic attributes of root systems for water and nutrient acquisition is root length density (RLD; cm of root length per cm^3 of soil) and its distribution relative to the tree trunk and irrigation system (Atkinson 1980). In general, fruit tree root systems under drip irrigation in semi-arid and arid regions most often adapt themselves to the relatively small soil volume wetted by the emitters, with limited horizontal distribution of soil water and roots in the area between tree rows. Levin *et al*. (1979) found that most roots in an apple orchard with a heavy clay soil in Israel were within 0.60 m of the drip line for the various irrigation frequencies and emitter rates (4 or 8 L/h) evaluated, and that root number was not affected by distance from the tree along the drip line in their high density orchard (i.e. 2 m between trees within a row). Similarly, ~80% of almond roots in an orchard with a silt loam-textured soil in semi-arid Spain developed within 1 m of the drip line and in the top 0.60 m of soil depth for an orchard with 4 drip emitters (4 L/h) per tree separated by 1-m intervals (Franco and Abrisqueta 1997). With grapevines, 54% of the variation in RLD could be explained by depth and distance from the drip line, with 80% of the roots in the top 1 m of soil (Stevens and Douglas 1994).

In olive, Fernández *et al*. (1991), using trenching and soil coring, found that most roots of var. *Manzanillo* were concentrated within 0.50 m of the drip irrigation line and in the top 0.60 m of soil depth in an orchard with 4 emitters per tree and a sandy loam-textured soil in southern Spain. Root distribution in a second orchard was more extensive due to a hard calcareous pan and finer textured soil, which allowed for greater lateral water movement. Very high values of RLD (i.e. up to 6 cm/cm^3) were measured in the first orchard near the tree trunk, but the remainder

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of the drip line had much lower values. These high values may have been related to root system characteristics from previous management practices, which persisted even 8 years after the orchard was converted to drip irrigation. On a whole-tree basis, average RLD values for this orchard were later estimated to be 0.224 cm/cm^3 within the rooting zone by Connor and Fereres (2005). In southern Italy, overall tree RLD for var. *Coratina* was much lower, with values of only 0.022 cm/cm^3 for trees receiving supplemental irrigation with a micro-sprinkler and 0.018 for trees receiving no irrigation based on whole-plant excavations (Dichio *et al*. 2002).

Because of the considerable range of RLD values previously reported in olive (i.e. an order of magnitude), the objectives of our study conducted in a new growing region in arid Argentina were to: (*1*) determine RLD values and root distribution relative to soil water content in three commercial orchards; and (*2*) estimate RLD values for the entire soil volume explored by the root systems in each orchard. Such information may be useful in later studies of root water uptake in high density orchards.

Materials and methods

Study areas

Three commercial orchards located in the growing region of Aimogasta (28°33′S, 66°49′W; 800 m elevation) in the Province of La Rioja in north-western Argentina were used to conduct the study. Mean annual rainfall in the area is ~100 mm with most of the rainfall occurring in the summer months, and annual reference evapotranspiration using the Penman-Monteith equation (Allen *et al*. 1998) is ~1600 mm. Mean daily average temperature is highest in January (28°C) and lowest in July (10°C).

Each of the three orchards had a different arrangement of emitters, tree spacing, and variety as shown in Fig. 1. The orchards are designated throughout the text, based on their emitter arrangements, as CE-4 (var. *Manzanilla fina*; 5 years old), E-4 (var. *Manzanilla fina*; 8 years old), and E-2 (var. *Manzanilla reina*; 5 years old). Details of the emitters for each orchard include: (*1*) 4 emitters per tree with the emitters being spaced continuously between trees along the drip line at 1.0-m intervals (continuous emitters-4; CE-4 orchard); (*2*) 4 emitters per tree with 2 emitters located on each side of the trunk and 2.0 m between emitters of neighbouring trees (emitters-4; E-4 orchard); and (*3*) 2 emitters per tree with 1 emitter located on each side of the trunk and 4.0 m between emitters of neighbouring trees (emitters-2; E-2 orchard). The distance between emitters in E-4 and E-2 was the same as in CE-4 (i.e. 1.0 m between emitters). The drip rate was 2 L/h in the CE-4 and E-4 orchards and 4 L/h for the E-2 orchard. Drip irrigation was used 10–12 months per year in the three orchards due to mild winter temperatures and paucity of rainfall throughout the year. A crop coefficient of ~0.7 was used to determine irrigation rate during most of the growing season, although specific information on water use requirements in our region was not available when our study was conducted (Rousseaux *et al*. 2008). Nitrogen and potassium fertilisation in these orchards was provided through the drip line after flowering in the spring of most years before our root sampling or when foliar nutrient deficiencies were noted.

The soil texture was loamy sand in the CE-4 orchard and gravelly to very gravelly sand in the E-4 and E-2 orchards. The

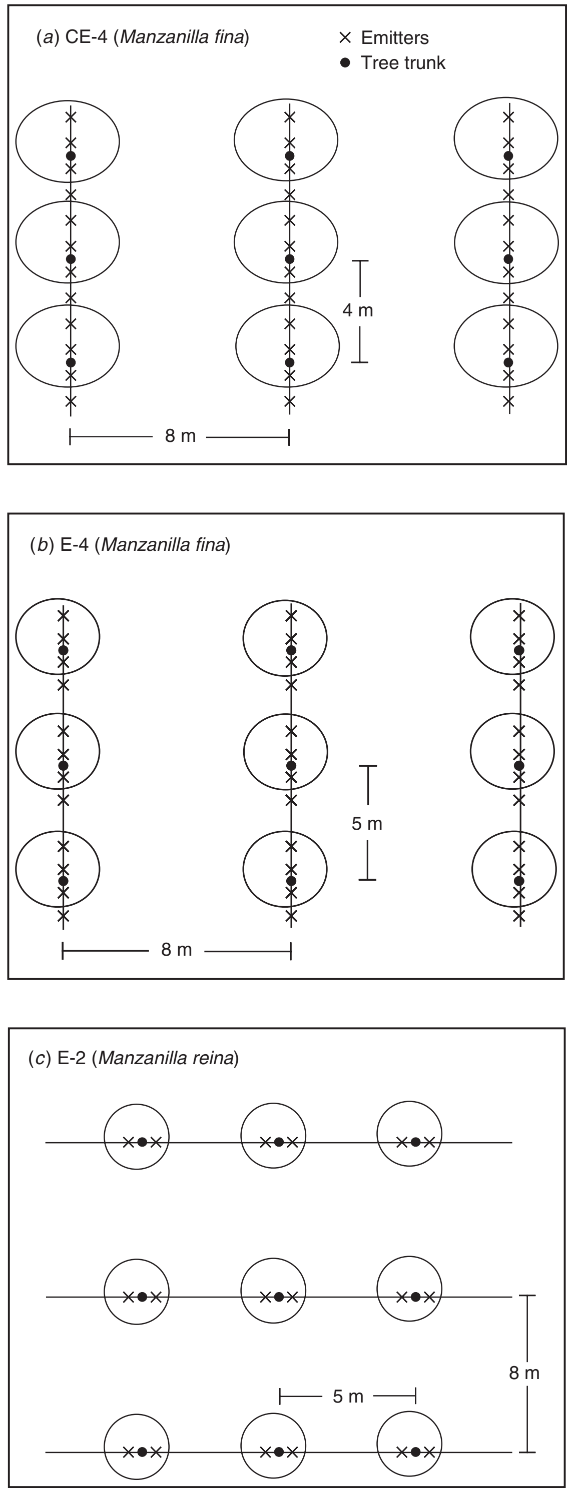

Fig. 1. Diagrams of the emitter arrangements and tree spacing in the (*a*) CE-4, (*b*) E-4, and (*c*) E-2 orchards. CE-4, 4 emitters per tree spaced continuously along the drip line at 1.0-m intervals; E-4, 4 emitters per tree with 2.0 m between emitters of neighbouring trees; E-2, 2 emitters per tree with 4.0 m between emitters of neighbouring trees. Tree canopy size in each diagram is proportional to actual size for each of the three orchards, and canopy position is off-centre from the tree trunk due to strong south-easterly winds. Row orientation is north to south in CE-4 and E-4 and east to west in E-2.

soils were all Entisols and no distinct changes in soil texture occurred in the 1.5 m of soil depth sampled in this study. Field capacity and wilting point in the sandy loam soil of the CE-4 orchard were ~0.15 and 0.05 by weight, respectively. Field capacity of the E-4 and E-2 orchards was under 0.10 by weight. Soil bulk density was not estimated during the study. Soil management did not include tillage, but weeds between tree rows were minimal due to the aridity of the region (<100 mm rainfall annually). Any weeds along the drip line were removed by hand in the months before the root sampling.

Sampling design

Soil auger samples were taken in February 2004 (i.e. mid-summer) just before harvesting for green table olives. The sampling was conducted along the drip line and along a north-west to south-east transect for 3 trees in each of the orchards (i.e. $n = 3$ replicates per orchard; Fig. 2). Along the drip line, samples were extracted at distances of 1.0 and 2.0 m from the trunk on both sides of the tree. The NW to SE transect was chosen because of a large asymmetry in the above-ground tree canopy created by strong prevailing south-easterly winds, and soil samples were taken at 0.5, 1.0, 1.5, 2.0, and 3.0 m from the tree trunk in both quadrants. These distances would correspond to a perpendicular distance of 0.35, 0.71, 1.06, 1.41, and 2.12 m from the drip line. The total soil volume extracted at each of the 3 soil sampling depths (0–0.5 m, 0.5–1.0 m, 1.0–1.5 m) for each sampling distance was 20.8 L given the 0.22-m-diameter of the soil auger. One litre of this total volume was then collected after mixing the soil to obtain a homogenous sample. The roots within these samples were mostly root segments rather than intact roots due to the destructive nature of sampling with a soil auger. In all cases, the orchards were being irrigated 3–4 times a week at the time of soil sampling, and the orchards had been irrigated less than

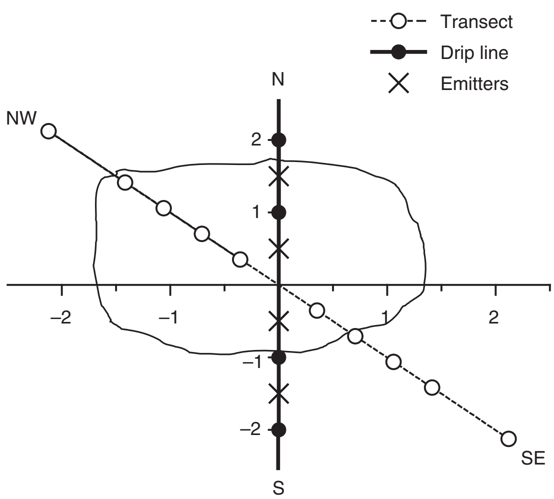

Fig. 2. Soil core sampling positions along the drip line (closed circles) and along a north-west to south-east transect (open circles). Two of the three orchards had 4 emitters per tree, with the drip line oriented north to south as shown in the figure, while a third orchard had 2 emitters per tree, with the drip line oriented east to west. Soil cores were taken along the drip line 1.0 and 2.0 m from the trunk for all three orchards. For the NW to SE transect, soil cores were extracted 0.5, 1.0, 1.5, 2.0, and 3.0 m from the tree trunk in both the NW and SE quadrants.

24 h before sampling. An individual irrigation event consisted of 166 L/tree over 18 h for the CE-4 and E-4 orchards and 64 L/tree over 9 h for the E-2 orchard based on tree size, number of emitters, and drip rate of the emitters, and in accordance with a crop coefficient of ~0.70.

Sample analysis

The soil samples were stored in several refrigerators at 5°C until they could be processed in the soil laboratory of the Centro Regional de Investigaciones Científicas y Tecnológicas (CRILAR-CONICET). Each 1-L sample was then divided into 2 subsamples for gravimetric soil water content (%) and RLD analysis. To determine soil water content, the subsamples were air-dried at 30−35°C for 7 days in the laboratory and several of these subsamples were then placed in a drying oven at 100°C to correct for differences between air-drying and oven-drying. This difference was less than 1% of soil humidity. For the RLD analysis, the roots were separated from the soil by passing fine soil particles through a 1.5-mm screen mesh under running water. Root loss through the mesh was minimal because the root segments tended to be fairly long (>10 mm in length) and the segments most often clumped together on the mesh surface. Any roots that passed through the screen were separated from the soil in a large plastic bowl positioned below the mesh. The roots, gravel, and remaining soil particles on the screen were then placed in a plastic container filled with water to separate the roots from the gravel. The roots and any remaining debris were then washed over the screen mesh a second time. The root samples were stored in plastic bags at 5°C for later processing.

To obtain a digital image of each root sample, the roots were spread out in a white tray (21 by 36 cm) containing a thin film of water, and a photograph was taken with a Nikon Coolpix 5400 digital camera (Nikon; Tokyo, Japan) mounted above the tray. A 5.0-cm-long reference marker was included along with the root sample to later correct root length and width for the camera magnification. The photographs were then adjusted in Adobe Photoshop 5.0 for brightness/contrast and other parameters. The final *.TIFF images were analysed using the Rootedge version 2.3 software package (Kaspar and Ewing 1997) to obtain the length and width of root segments individually and cumulatively for each sample. This software is available without charge from the United States Department of Agriculture and has been shown to give nearly identical results in comparison with a commercially available image analysis program (Coelho and Or 1999). Lastly, all root samples were dried in an oven at 60°C and weighed to determine dry mass. Unusually large coarse root fragments (>10 mm diam.) were removed from a few samples to avoid unrepresentative results.

Data analysis

Nested-factorial analyses of variance were performed separately for the drip line and the NW to SE transect of each orchard to assess the effects of direction from the trunk, soil sampling depth, and distance from the trunk on RLD, dry root mass, and gravimetric soil water content (SWC; %), using SAS statistical software (SAS Institute; Cary, NC, USA). Percentage of root length as fine roots (<1 mm) was also evaluated with analysis of variance after categorising the length of individual root segments obtained from the Rootedge program as being 0–1, 1–2, or >2 mm in diameter. Simple linear regression analyses were conducted for each orchard to assess relationships between soil water content and RLD and between dry root mass and RLD using GraphPad Prism software (San Diego, CA, USA). Possible relationships between RLD and the surface distance from either the nearest emitter or the trunk to the sampling positions in Fig. 2 were also evaluated in each orchard. Radial distance from the nearest emitter or the trunk to these same positions *v.* RLD was similarly assessed. Radial distance was defined as the hypotenuse between surface distance from the nearest emitter or the trunk to a given sampling position and soil depth at the midpoint of the soil sample. The data points were fit to non-linear, exponential decay functions using the same software (i.e. GraphPad Prism).

Values of RLD averaged over the entire rooting zone were then calculated using the exponential decay relationship for each orchard between radial distance from the nearest emitter and RLD. Total root length per tree (km/tree), root length per ground area including the inter-row space (km/m^2), and total root mass per tree (kg/tree) were also estimated. Whole-tree leaf mass (kg/tree) and leaf area (m^2/tree) were approximated from tree canopy volume (m^3) measurements taken at the time of the soil auger sampling (i.e. February 2004) and later measurements of specific leaf mass (253 g/m^2) and leaf area density (leaf area per canopy volume; 2.8 m^2/m^3) in a similar *Manzanilla fina* orchard. Leaf area density was estimated non-destructively using leaf counts within a 20-cm-sided cube and with a Li-Cor 2000 Plant Canopy Analyzer (Lincoln, NE, USA) such as in Villalobos *et al*. (1995). The trees in these orchards had not been pruned for several years before the measurements.

Results

Root and soil water distribution

Both RLD and SWC along the drip line decreased markedly with soil depth in the CE-4 orchard ($P < 0.001$), with most of the roots being located in the top 0.5 m depth (Fig. 3*a*, *b*). In contrast, values of both variables remained fairly constant with distance from the trunk at a given soil depth, likely due to the continuous nature of the emitters along the drip line. Additionally, no effect of direction was seen in that RLD and SWC were not different when comparing the north and south sides of the trees along the drip line. Similar to the CE-4 orchard, both RLD and SWC decreased with soil depth in the E-4 orchard ($P < 0.001$) (Fig. 3*c*, *d*). However, a significant interaction term between soil depth and distance from the trunk along the drip line was observed, with RLD and SWC both decreasing between 1.0 and 2.0 m from the trunk at the 0–0.5 m depth, but not at lower depths ($P < 0.05$). This indicates that RLD and SWC near the soil surface (i.e. upper 0.5 m) were strongly affected by the position of the emitters, with both variables having high values between the two emitters and much lower values even 0.5 m from the last emitter along the drip line. As with the other two orchards, RLD ($P < 0.001$) and SWC ($P < 0.05$) decreased with soil depth at the E-2 site (Fig. 3*e*, *f*). The effect of soil depth also differed with distance from the trunk ($P < 0.001$) for RLD, as in the E-4 orchard, although the results were not symmetrical on each side of the tree as indicated by a significant direction × soil depth term ($P < 0.05$). Soil water content did not show any significant interaction terms at this site.

For the NW–SE transect, all three orchards showed a strong decrease in RLD with soil depth ($P < 0.005$ in all cases) (Fig. 4*a*, *c*, *e*), although the soil depth × distance from the trunk interaction term was also significant in each orchard ($P < 0.001$). This indicates that RLD decreased greatly with distance from the trunk in the upper 0.50 m of soil depth, but that the values of RLD were relatively independent of distance below 1.0 m soil depth. Soil water content followed a similar pattern to RLD in the CE-4 and E-2 orchards, with SWC decreasing with soil depth ($P < 0.01$) (Fig. 4*b*, *f*). Although soil depth and distance from the trunk did not show a significant interaction in either of these orchards for SWC (*P*-values of 0.08 and 0.13), there was still some tendency for SWC to decrease with distance from the trunk in the upper 0.5 m depth and to a lesser extent at lower depths. In the E-4 orchard, there was a significant decrease in SWC with depth ($P < 0.05$), but there was also a strong main effect of direction, with SWC being greater to the north-west of the tree relative to the south-east ($P < 0.001$) (Fig. 4*d*).

Regressions between RLD and other variables

Linear regressions between SWC and RLD were significant for all three orchards ($P < 0.001$ in all cases), indicating that root exploration was largely confined to the soil volume wetted by the emitters in this arid region (Table 1). Significant relationships were also found between dry root mass (DRM) and RLD ($P < 0.001$). These DRM *v.* RLD relationships predominately represent fine roots (<2 mm diam.) rather than total roots in that very large coarse roots (>10 mm) were removed from the two samples. The regression lines for DRM *v.* RLD of the two orchards (i.e. CE-4 and E-4) containing var. *Manzanilla fina* had similar slopes and intercepts ($P > 0.05$), while the regression of the E-2 orchard with *Manzanilla reina* had a lower slope ($P < 0.001$). This lower slope occurred because its roots were of somewhat greater diameter (i.e. more root mass per root length) than the roots of *Manzanilla fina* (data not shown). Given the highly significant relationships between DRM and RLD, DRM could likely be used to estimate RLD for a given variety in future studies.

Root length density was strongly related to the radial distance from the nearest emitter when non-linear, exponential regressions were used (Fig. 5*a*). Radial distance from the nearest emitter is defined as the hypotenuse between surface distance from the nearest emitter and soil depth at the midpoint of the soil sample. The r^2 values were 0.94 for CE-4, 0.49 for E-4, and 0.67 for the E-2 orchard. Much lower r^2 values occurred between surface distance from the nearest emitter to the sampling positions and RLD because individual sampling points may be near an emitter along the soil surface, but be located at soil depths (i.e. 1.0–1.5 m) where RLD is always low (Fig. 5*c*). Additionally, little or no evidence of relationships between either radial or surface distance from the trunk with RLD was found (Fig. 5*b*, *d*).

Whole-tree root system estimates

To further evaluate RLD, average values of RLD within the rooting zone and of the three sampled soil depths were estimated for each orchard using the relationships of radial distance from the nearest emitter mentioned above. In the rooting zone, the average RLD values were 0.48 (CE-4), 0.41 (E-4), and 0.19 cm/cm^3 (E-2),

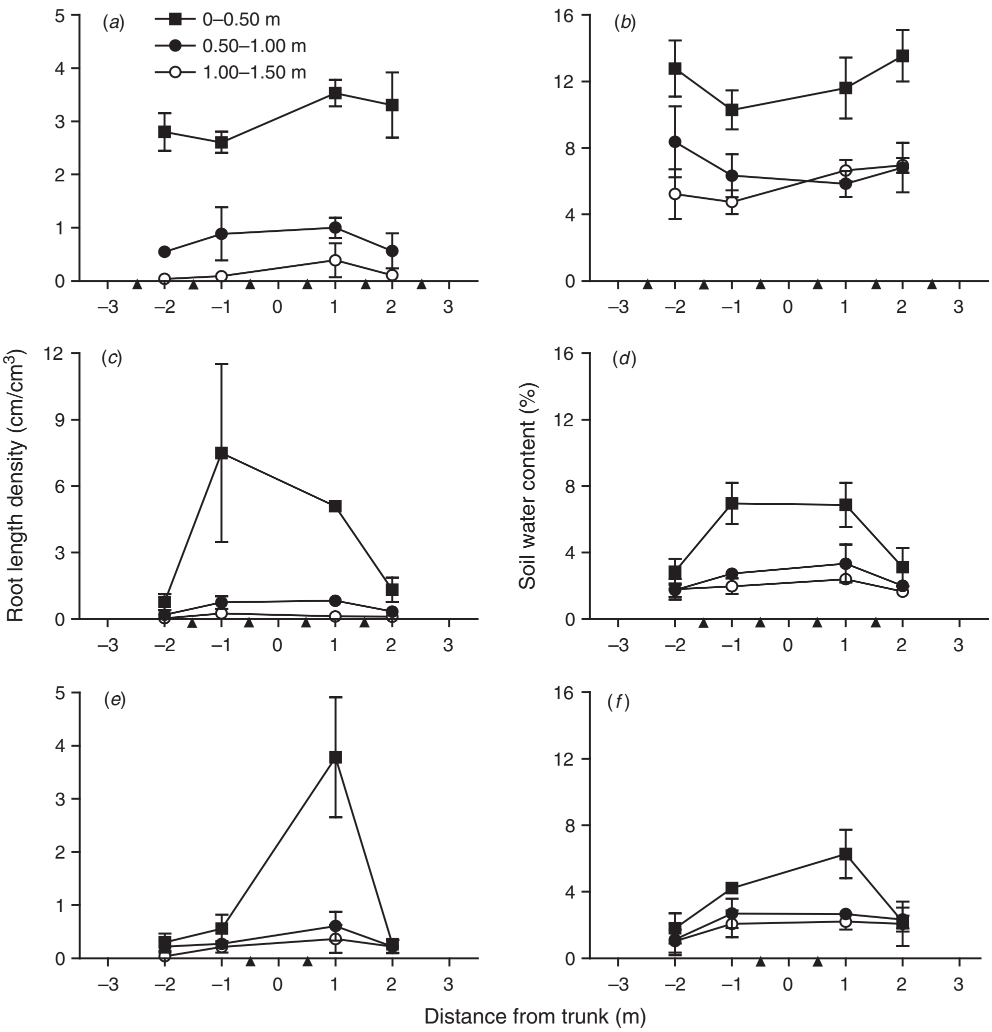

Fig. 3. Root length density and gravimetric soil water content distribution with distance from the trunk and soil depth (0–0.50, 0.50–1.00, 1.00–1.50 m) for the drip line in the (*a*, *b*) CE-4, (*c*, *d*) E-4, and (*e*, *f*) E-2 orchards. The abbreviations for the orchards are defined in Fig. 1. Negative distances along the *x*-axis indicate either north or west of the trunk and positive distances indicate either south or east of the trunk, depending on row orientation. Emitters are shown as closed triangles. Six emitters rather than four are shown for the CE-4 orchard to indicate the continuous nature of the emitters along the drip line. Symbols denote the mean ± s.e. ($n = 3$ trees).

with 70–75% of RLD located in the upper 0.5 m of soil depth in each of the three orchards (Table 2). Approximately 20–25% of RLD was estimated to be at the 0.5–1.0 m depth and only 5% was below 1.0 m. Total root length per tree was 115 (CE-4), 124 (E-4), and 57 km/tree (E-2) (Table 3). Further calculations indicated root length per ground area values (km/m^2) ranging from 1.4 to 3.6, depending on the orchard. These values represent total ground area including inter-row spacing and not just the rooting zone. Root length per leaf area values (km/m^2) were 1.8–3.5, while root mass to leaf mass ratios were 0.73–1.32. Lastly, leaf area values ranged from 31 to 52 m^2/tree, with the CE-4 orchard having the greatest values, possibly due to finer soil texture and more use of fertiliser at this site despite this orchard having younger trees (5 years old) than those in the E-4 orchard (8 years old).

Discussion

The development of new olive-growing regions in the Southern Hemisphere such as Australia and Argentina where conditions are generally drier than those in the Mediterranean basin along with an overall, global modernisation of management techniques has resulted in a renewed focus on many aspects of olive production (Nuberg and Yunusa 2003; Connor 2005; Rousseaux *et al.* 2008). Our findings in three commercial orchards in north-western Argentina using drip irrigation systems indicate that root distribution is tightly coupled with soil water distribution. Overall, root distribution appears to reflect emitter arrangement even in fairly young olive trees (i.e. 5–8 years old), although other factors such as soil texture, emitter discharge rate, and variety likely also have important roles. For example, RLD maintained consistently high values (2.5–3.5 cm/cm^3) in the upper 0.5 m of

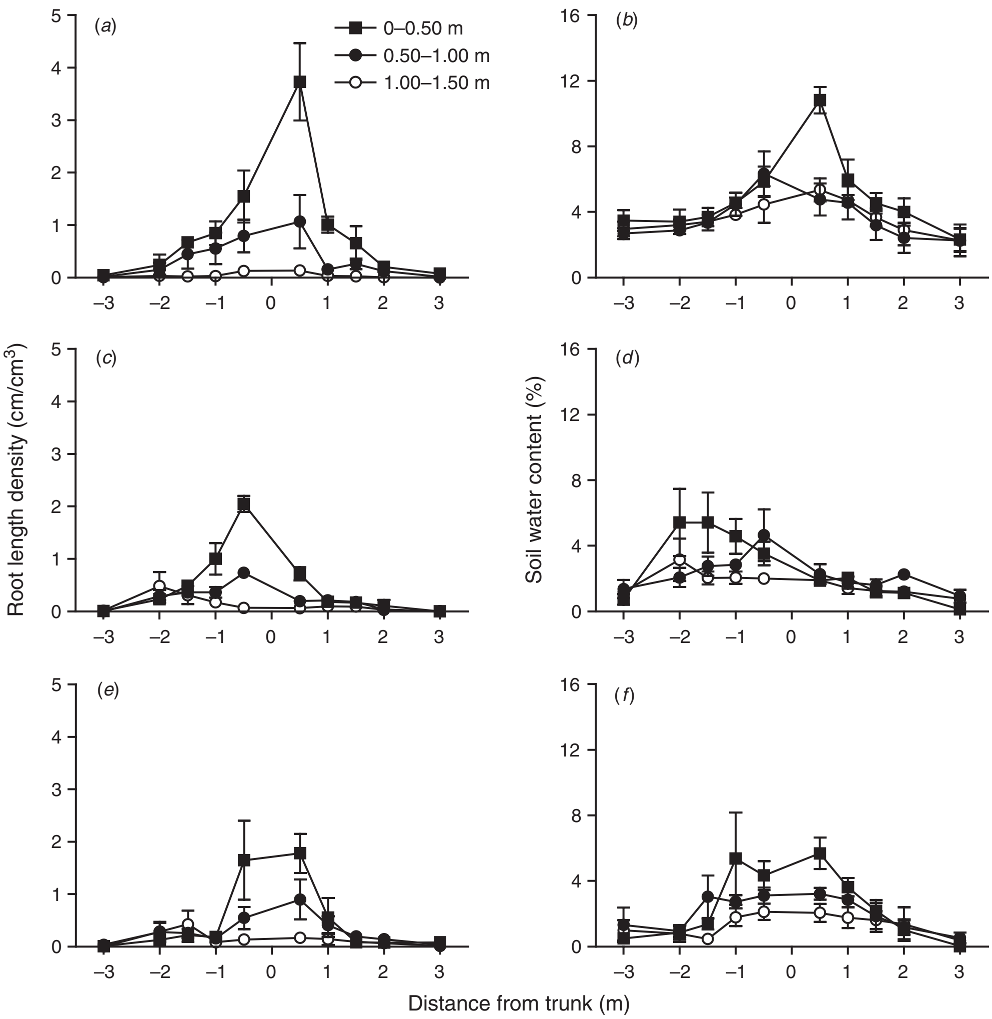

Fig. 4. Root length density and gravimetric soil water content distribution with distance from the trunk and soil depth (0–0.50, 0.50–1.00, 1.00–1.50 m) for the NW–SE transect in the (*a*, *b*) CE-4, (*c*, *d*) E-4, and (*e*, *f*) E-2 orchards. The abbreviations for the orchards are defined in Fig. 1. Symbols denote the mean ± s.e. ($n = 3$ trees).

Table 1. Linear regressions between gravimetric soil water content (SWC, %) and root length density (RLD, cm/cm^3) and between dry root mass (DRM, g) and RLD

The number of data points for each orchard including all sampling distances and depths was $n = 42$. Each point represents the mean of the three trees in each orchard. Orchard abbreviations are the same as in Fig. 1. $P < 0.001$ in all cases

Variables	Orchard	Equation	r^2 value
SWC (%) *v.*	CE-4	RLD = 0.32 (SWC) – 0.97	0.78
RLD	E-4	RLD = 0.66 (SWC) – 0.99	0.55
	E-2	RLD = 0.33 (SWC) – 0.32	0.53
DRM *v.*	CE-4	RLD = 1.08 (DRM) + 0.053	0.90
RLD	E-4	RLD = 1.13 (DRM) – 0.025	0.91
	E-2	RLD = 0.79 (DRM) – 0.015	0.85

a loamy sand-textured soil over the length of the drip line when emitters were spaced continuously at 1-m intervals (CE-4 orchard), but decreased strongly from 5–7 cm/cm^3 between emitters to 0.8–1.3 cm/cm^3 at a distance of only 0.5 m from the last emitter for each tree in the E-4 orchard (4 emitters per tree) with its gravelly sand soil. Similar patterns were seen in terms of soil moisture. Both of these orchards contained trees of var. *Manzanilla fina*.

Similar to our study, Fernández *et al*. (1991) also reported high values of RLD (i.e. up to 6 cm/cm^3) in *Manzanillo* olive in the upper 0.2 m of a loamy sand soil under drip irrigation based on soil auger sampling, but agricultural practices several years earlier before conversion from dry farming to drip irrigation may have contributed to these values. In contrast, Palese *et al*. (2000) found maximum RLD values of only 0.069 for var. *Coratina* in the upper portion of a medium-textured, loam soil in young trees (3 years old) irrigated with micro-jets using the minirhizotron technique. The fairly high RLD values along the drip line in our study likely resulted from the narrow wetted bulb created by the lack of rainfall in the region (i.e. ~100 mm/year) and the very coarse soil texture in these orchards. Seventy percent of RLD was located within 0.5 m of the drip line and over 90% within 1.0 m based on whole-tree estimates. As indicated by Levin *et al*. (1979), the main feature that characterises drip irrigation of fruit

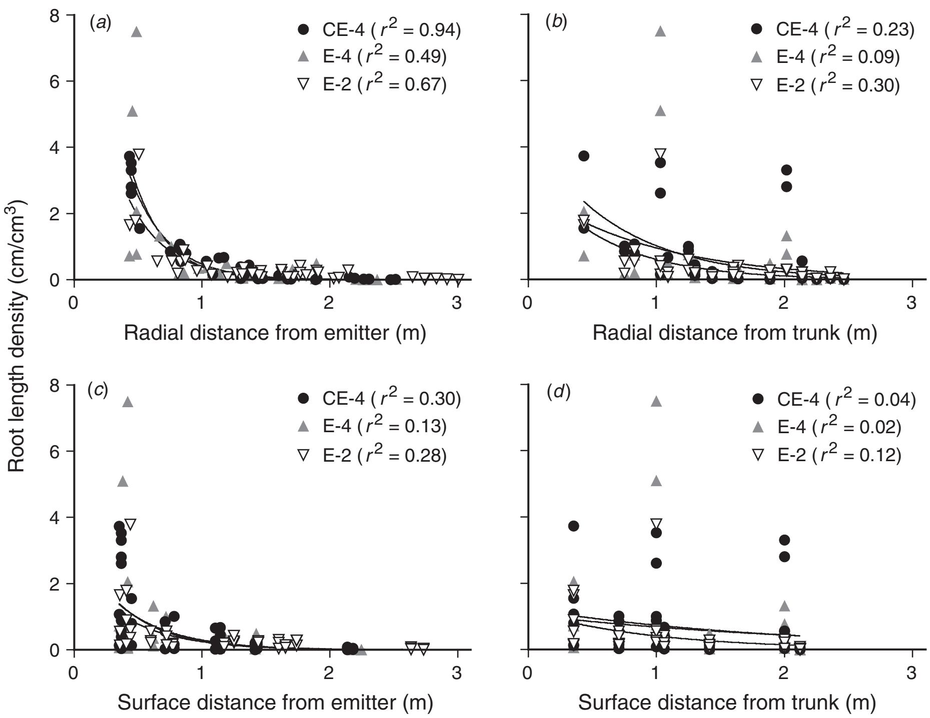

Fig. 5. (*a*) Root length density in relation to radial distance from the nearest emitter, (*b*) radial distance from the trunk, (*c*) surface distance from the nearest emitter, and (*d*) surface distance from the trunk for the CE-4, E-4, and E-2 orchards. The abbreviations for the orchards are defined in Fig. 1. The exponential decay equations for radial distance from the nearest emitter (r) *v.* RLD are: RLD = 13.6exp(–0.034r) for CE-4, RLD = 18.5exp(–0.038r) for E-4, and RLD = 9.7exp(–0.032r) for the E-2 orchard.

Table 2. Average root length density (RLD, cm/cm^3) values for the entire soil volume explored by the root systems in each orchard and for the individual sampling depths (0–0.5, 0.5–1.0, 1.0–1.5 m)

Percentage values that each soil depth represents of total RLD are given in parentheses. Orchard abbreviations are the same as in Fig. 1

Orchard	Whole-tree RLD	RLD values at given soil depths (m)		
		0–0.5	0.5–1.0	1.0–1.5
CE-4	0.48	1.05 (73%)	0.32 (22%)	0.077 (5%)
E-4	0.41	0.95 (76%)	0.24 (20%)	0.048 (4%)
E-2	0.19	0.40 (69%)	0.14 (24%)	0.039 (7%)

Table 3. Some estimated whole-tree root system and tree canopy parameters

Orchard abbreviations are the same as in Fig. 1

Parameter	CE-4	E-4	E-2
Root length (km/tree)	115	124	57
Root length/ground area (km/m^2)	3.6	3.1	1.4
Root mass (kg/tree)	9.5	11.6	7.8
Leaf mass (kg/tree)	13.1	8.8	7.8
Leaf area (m^2/tree)	52	35	31

trees is the limited horizontal distribution of water in the area between tree rows, and this is especially the case in arid zones (Franco and Abrisqueta 1997). Fernández *et al.* (1991) also noted a narrow wetted bulb and similarly narrow distribution of olive roots in a loamy sand soil under Mediterranean conditions, but not for a more clayey soil with an underlying hard pan.

In addition to the concentration of roots horizontally, over 70% of the roots were located in the upper soil depth (0–0.5 m). Even though the absolute values of soil moisture content in the three orchards in our study were low due to the coarse soil textures (i.e. loamy sand and gravelly sand), the orchards were irrigated 3–4 times per week for most of the year and SWC was rarely allowed to decrease much below field capacity even in the upper 0.25 m of soil depth. Fernández and Moreno (1999) have suggested that the root system of olive where most of the main roots grow more or less in parallel to the soil surface may have evolved for absorbing the water of light and intermittent rainfalls that commonly occur under Mediterranean conditions rather than for taking up water from deep layers.

Significant relationships between RLD and SWC such as those found in each of the three orchards for the entire soil profile (0–1.5 m) have also been observed in apricot (Ruiz-Sánchez *et al.* 2005) and in annuals such as corn (Coelho and Or 1999) under drip irrigation. In contrast, Michelakis *et al.* (1993) found that root density and SWC were not related in avocado likely due to oxygen being limiting near the emitters in the fine-textured, clay soil where the study was conducted. Indirect evidence from other studies with olive shows that root growth responds positively to irrigation. After 7 years, Dichio *et al.* (2002) observed that the soil volume explored by roots was 34% greater and RLD was 22% greater under irrigated than non-irrigated conditions. Additionally, root growth of olive increased with the initiation of drip irrigation at the beginning of the summer in southern Spain as measured using mini-rhizotrons (Fernández *et al*. 1992). Thus, it appears likely that RLD and SWC will be closely associated in olive orchards, although this relationship may be affected by soil texture or other variables.

Spatially, RLD decreased exponentially with radial distance from the nearest emitter (i.e. a combination of surface distance and soil depth) in all three orchards. In contrast, little or no relationship between RLD and radial or surface distance from the trunk was found, although high RLD values within decimeters of the trunk may have been missed by our sampling protocol. Similarly, Stevens and Douglas (1994) found that horizontal surface distance out into the row from the vine butt and soil depth were not good predictors alone of RLD in grape, but that measures of radial distance such as radial distance from the nearest emitter could account for more than 50% of variation in RLD. Because of the relationship between RLD and radial distance from the nearest emitter in our study, RLD remained fairly constant if emitters were placed continuously at a given interval along the drip line as seen in the CE-4 orchard. Levin *et al*. (1979) also found quite uniform root concentrations along the tree row (i.e. drip line), although these concentrations differed with irrigation frequency, emitter spacing, and emitter output. Fernández *et al*. (1991) did not observe uniform RLD values along the drip line in olive, but management practices previous to drip line conversion may have influenced the results as mentioned above.

Whole-tree estimates of RLD, such as average RLD within the rooting zone, are needed to better understand the potential capacity of olive trees to absorb water and nutrients in high density, well-irrigated orchards. Although average RLD values may vary considerably due to the irrigation method used, the range of previously reported values from 0.022 cm/cm^3 under micro-jet irrigation (Dichio *et al*. 2002) to 0.224 cm/cm^3 under drip irrigation (Connor and Fereres 2005 using data from Fernández *et al*. 1991) is quite broad. In contrast to RLD, leaf area density values (i.e. leaf area/canopy volume) may range from 1.1 to 2.7 m^2/m^3, but typical values can be reasonably well defined as being between 1.5 and 2.0 m^2/m^3 (Villalobos *et al*. 1995, 2006).

Our values for average RLD (0.19–0.48 cm/cm^3) within the rooting zone in three orchards under drip irrigation in arid north-western Argentina were of the same magnitude as those estimated from Fernández *et al*. (1991) under drip irrigation in southern Spain. Root length per leaf area in the three orchards (1.8–3.5 km/m^2) also showed similarities to the values (2.2–2.7 km/m^2) obtained from Fernández *et al*. (1991). Additionally, the range of root mass to leaf mass ratios (0.73–1.32) in our study is consistent with values reported for potted olive plants and young trees (2 years old) in the field (Mariscal *et al*. 2000; Bacelar *et al*. 2007; Gómez del Campo 2007).

Currently, RLD values provide some insight into the relationships between the aerial and below-ground portions of olive trees. However; further research is needed to evaluate how to optimise drip emitter arrangements to maintain tree productive performance and save irrigation water in high density orchards. Studies of olive root lifespan, turnover, respiration, construction and maintenance costs, and efficiency (i.e. the ratio of water or nutrient benefit to carbon cost over root lifetime) would provide basic information towards this goal.

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