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Tree-induced changes in a terra rossa soil under olive. Observations from an integrated field study

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Abstract: A range of indicators including chemical, physical, morphological, and clay mineral properties were investigated to support an integrated evaluation of the changes induced by a long established olive grove on a red Mediterranean soil. The study area was located in Sardinia (Italy). Two soil profiles were studied in a site where land use had remained unchanged for the previous 150 years: one under the canopy and around the trunk of an olive tree and one between the trees. Chemical analyses including organic matter fractions were performed by horizon. Undisturbed soil samples were collected from aggregates for thin section and scanning electron microscopy (SEM) analyses, complemented by clay mineralogy. Relative compaction was observed in tree topsoil due to the pressure of the anchoring roots. Lower compaction, higher porosity, and less developed micro-aggregates were observed in deeper horizons in relation with the loosening action induced by roots. Sharper vertical chemical gradients were determined under the tree. Stress features were observed in thin sections from all the horizons. Traces of smectite were determined as indicator of past shrink–swell processes suggesting that the present-day dominance of illite-like minerals might be explained by transformation of smectite induced by pedogenesis and by the long-lasting K-enriching action of the plants. Our findings indicate the need to undertake more systematic, integrated, and comparative future research on this subject.

Key words: Micromorphology, roots, SEM, stress features, XRD, illite-like minerals

1. Introduction

The red soils of the Mediterranean basin, also known as terra rossa (Rhodic or Chromic Luvisols according to IUSS Working Group WRB, 2015), have traditionally been allocated to permanent crops such as olive groves. Olive (*Olea europea* Linnaeus) is an important component of the Mediterranean cultural landscapes and a primary element of cultural identity for the populations of the region (Loumou and Giourga, 2003). In Sardinia (Italy) the olive has been cultivated since ancient times. At present, the extent of the olive grove area is relatively limited and mainly concentrated in a small number of places, particularly around the city of Sassari (Barbera and Dettori, 2006), where terra rossa is the dominant soil type.

We formulated the hypothesis that the long-established olive groves and the associated farming practices have influenced the development of the present-day terra rossa soil features, particularly in terms of macro- and microstructure, biologic activity, fertility, and mineral composition. Since only a few studies have analyzed these aspects and none of them was based on an integrated research approach, the aim of the present article was to contribute to filling this knowledge gap. The specific objective of the research was to analyze the changes induced by a long-established traditional olive grove on a red Mediterranean soil, under the action of root and plant development, with special focus on morphological features. To achieve this objective a range of indicators including morphological, micromorphological, physical, chemical, and clay mineral properties were investigated to support a more integrated evaluation.

1.1. Soil morphological changes induced by root development

The relationships between soil and tree root development are a complex research subject due to the multiple dynamic interactions between the soil matrix, the roots, and the soil biota (Six et al., 2004). Many processes acting at the root–soil interface have been thoroughly investigated (Young, 1998; Gregory, 2006). The following paragraphs briefly review the (mostly outdated) literature focusing

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on the effects of root development on soil structure and microstructure.

Root development exerts a direct mechanic effect on soil due to axial and radial growth pressure (Misra et al., 1986). According to Dexter (1987), as the root expands, the pressure on the adjacent soil increases the soil bulk density and decreases soil porosity. On the other hand, Gibbs and Reid (1988) observed that root penetration results in the enlargement of pores or in the creation of new ones. Root networks also enhance soil porosity as well as soil aggregation through direct entanglement of particles (Tisdall and Oades, 1982). Statistical correlations were found between root length and/or mass and soil aggregation (Miller and Jastrow, 1990); however, Carter et al. (1994) argued that the overall influence of root penetration on aggregation depends on root architecture. It is known that roots can improve aggregation through water uptake, causing localized temporary drying of the soil, which promotes binding of root exudates on clay particles (Reid and Goss, 1982). The repeated wetting/drying cycles would also result in smaller aggregates (Materechera et al., 1992, 1994) compared to the surrounding soil. Limited information is available about the microstructural effects of root development, although the subject is relatively old (e.g., Blevins et al., 1970), and no studies specifically address these micromorphological effects in the olive root zone. Krebs et al. (1993) observed that different root systems of plant species may result in different soil fabric. A reorganization and orientation of the clay particles was observed in the immediate vicinity of roots by Dorioz et al. (1993), where the formation of microaggregates around the roots was linked to the increased bulk density within a 50–200 µm zone. Clemente et al. (2005), studying the effect of *Eucalyptus grandis* roots on a well-structured Oxisol (Kandiudox) in Australia, found compaction and porosity reduction to distances greater than 4 cm from soil–root contact for root diameters >3.5 cm, along with clay-oriented features, microfractures, and microslickenside effects on the root–soil contact surface. Recent studies were carried out by Kodešová et al. (2006), who described macropores created by roots and soil microorganisms in a Haplic Luvisol, quantifying the impact of these on soil water retention properties.

2. Materials and methods

2.1. Study area

The study area was located in an olive grove near Sassari (NW Sardinia, Italy; 456228 E and 4509139 N UTM WGS 84), where the land use had remained unchanged for the previous 150 years (Figure 1). Elevation of the study area is about 110 m a.s.l. and the landscape is flat to gently undulating. The bedrock is Miocene yellowish-brown hard crystalline limestone. The average annual rainfall is around 600 mm and the climate is Mediterranean

Figure 1. Location of the study area, in Sassari municipal territory (Sardinia, Italy).

semiarid according to Emberger (Daget, 1977). Two soil profiles were dug, taking into account the characteristics of the olive canopy and root system (according to Fernandez et al., 1991 and Dichio et al., 2002). The first was dug under canopy and around the trunk of an 80-year-old olive tree. The second was between the trees, at about 3 m from the previous one. The trees had been planted by hand and no leveling had been carried out in the past. The soil was subjected to manual farming practices, including annual green manuring. The profiles were described in the field (Table 1) according to FAO (2006) and classified as Haplic Endoleptic Luvisols (Hypereutric, Chromic) according to the IUSS Working Group WRB (2015). Their horizon sequence is Ap1-Ap2-Bt1-Bt2-R.

2.2. Physical and chemical analyses

Horizons were sampled for physical and chemical laboratory analyses carried out on the fine earth fraction (<2 mm) of air-dried bulk samples. The following chemical analyses were performed according to Società Italiana della Scienza del Suolo (2000): organic carbon (OC; Walkley–Black method); total nitrogen (N; Kjeldahl method); pH (in water and in KCl solution), available phosphorus (P_2O_5; Olsen method); total carbonate content (Carb; by Dietrich-Fruehling calcimeter); CEC and exchangeable cations (CEC; Ca^{++}; Mg^{++}; Na^+; K^+; Cl_2Ba and triethanolamine method); organic matter fractions (total extractable carbon, TEC; humic acids, HA; and fulvic acids, FA). The following granulometric classes were used for particle size analysis: 2.0–1.0 mm, very coarse sand; 1.0–0.5 mm, coarse sand; 0.5–0.25 mm, medium sand; 0.25–0.02 mm, fine and very fine sand; 0.02–0.002 mm, silt; <0.002 mm, clay. Rock fragments (>2 mm) and coarse sand fractions were determined by wet sieving, whereas the finer granulometric fractions were determined by means of the wet sieving and pipette method, according to Società Italiana della Scienza del Suolo (1997).

2.3. Micromorphology

Undisturbed samples, including both large aggregates and small ones clinging to fine roots and biostructures built by annelids (worm cast), were collected for micromorphological characterization using thin section and scanning electron microscopy (SEM) analyses. Thin sections were described according to Bullock et al. (1985) and Stoops (2003). SEM images were obtained by a Philips XLS-30 Scanning Electron Microscope from small undisturbed lumps about 1 cm in diameter. The micromorphological analysis for the comparison of the soil in the root zone and between the trees focused on the microstructure (MS) and the microstructural units (MSUs) in different horizons (aggregate development, porosity, b-fabric, and bioturbation).

2.4. Clay minerals

Four horizons (the Ap1 and Bt1 of each profile) were selected for determination of the dominant clay minerals. Clay size fractions were subjected to XRD analysis. The samples were prepared as oriented specimens on glass slides in 1:4 $MgCl_2$:clay suspensions, where two slides were saturated with Mg++, one was treated with ethylene glycol, and both were scanned from 3 to 13 (2 theta). The XRD semiquantitative analysis was conducted using a Bruker AXS D8 Advance diffractometer.

3. Results and discussion

3.1. Field observations

Frequent biological activity by earthworms was observed in both profiles, and especially under canopy, in Profile 1 (Table 1). In Profile 1 (under the tree) the main roots are denser in the Ap1 and Bt1 horizons. The Ap2 horizon

Table 1. Schematic field description of the studied profiles.

Horizon and Depth (cm)	Description of Profile 2 (between the trees)	Variants observed in Profile 1 (under the tree)
Ap1 P1: 0–10 P2: 0–10	Brown to dark brown (7.5 YR 4/4). Moderate, fine to medium, slightly hard subangular blocky. High porosity (many very fine and few medium pores). Frequent fine medium and common coarse roots. Common biological activity (insects and earthworms). Abrupt, smooth boundary.	Moderate, fine to medium, soft to slightly hard subangular blocky. Medium porosity (many very fine and few medium pores). Common fine medium and very few coarse roots.
Ap2 P1: 10–20 P2: 10–30	Brown to dark brown (7.5 YR 4/4). Strong, medium, hard, subangular and angular blocky. Medium porosity (fine pores). Common fine and medium roots. Common biological activity (insects and earthworms). Abrupt, smooth boundary.	Brown to dark brown (7.5 YR 4/3). Strong, medium, friable subangular blocky. Medium porosity (many very fine and fine pores). Common, fine, and few medium roots.
Bt1 P1: 20–49 P2: 30–50	Yellowish red (5 YR 4/6). Strong, coarse to very coarse, hard angular blocky. Abundant distinct clay coatings on pedfaces and in voids. Few very fine pores. Common to few fine roots. Common biological activity. Abrupt, smooth boundary.	Strong, coarse, hard angular blocky. Many distinct clay coatings on pedfaces and in voids. Few fine, and few medium roots. Rare biological activity.
Bt2 P1: 49–80/85 P2: 50–80/95	Reddish brown to yellowish red (5 YR 4/5). Strong, coarse, hard angular blocky. Abundant distinct clay coatings on pedfaces and in the voids. Few very fine pores. Few fine and very few medium roots. Rare biological activity. Abrupt, wavy boundary.	Reddish brown (5 YR 4/4). Many distinct clay coatings on pedfaces and in voids. Abrupt, smooth boundary.
R	Miocene limestone.	Miocene limestone.

is compacted, most likely due to the anchoring action of the main surface roots in Ap1, despite the vigorous faunal activity (frequent faunal channels, 0.5 cm diameter) in this horizon. Roots range from thick/main (1–5 cm diameter) to medium (0.5–1 cm) and fine (<0.5 cm). The density of the fine roots is higher in the Bt2 horizon, which is not compacted. The main roots are horizontal and in minor areas of Ap2 microlaminations were observed parallel and in between the roots. Laminae are 0.5–1 cm apart from one another in the vertical direction and show a horizontal length of about 10 cm. The main roots seem to limit the uniformity of the bioturbation processes in the profile. Earthworms appear to be sheltered under the main root system where channels (1–1.5 cm diameter) are well preserved in the Ap1, Ap2, and Bt1 horizons. In Profile 2 (between the trees) part of the Ap1 horizon (0–10 cm) is compacted, most likely due to the mechanical effect of human and machinery traffic. The Ap2 horizon (10–20 cm) is more abundant in fine roots, whereas the upper part of the Bt1 (20–28 cm) is almost without roots. The lower part of the Bt1 (40–50 cm) is a more compact sublayer with intense bioturbation.

3.2. Physical and chemical analyses

The amounts of clay (Table 2) gradually increase with depth in both profiles. They are relatively similar in the A and B horizons, likely as a result of homogenization by vigorous bioturbation. The relative uniformity of the clay fraction in the profile points to the maturity of the profile and the long enduring pedogenic processes.

Organic carbon and N show an abrupt change from A to B horizons in both profiles (slightly more gradual in profile 2), where OC decreases rapidly from more than 4% in Ap1 to around 1% in Bt2. The same trend is followed by C/N, highlighting a greater degree of humification in the B horizons. The higher amounts of OC in the surface horizon of both profiles may be due to leaf and fruit fall together with manuring.

The lower pH of the surface horizon (around 7 in the A horizons compared to around 8 in the B horizons) is most likely due to more intense decalcification (dissolution of the rare primary marine limestone fragments to form the rare to moderate secondary calcite nodules identified in thin sections in the Bt horizons of both profiles). The high amount of P in the surface horizons (Ap1), especially in profile 1, is most probably due to the leaf and fruit fall, and to shallow plowing by small garden equipment inducing more intense decomposition of the organic matter, along with possible past fertilization (not applied recently). The higher exchangeable potassium content in the upper horizons is most likely due to the high K content of the olive fruits, which varies from 13 to 17 g kg^{-1} (Nergiz and Engez, 2000).

The higher fulvic acid contents than humic in both profiles indicate an increase in carbohydrates (enhancing FA formation) by leaf fall. The higher amounts of HA in profile 1 than in profile 2 reflect its higher OC contents. The HA contents clearly decrease with depth only in profile 1, parallel to OC, whereas the FA contents fluctuate with depth in both profiles, supporting the view of a vigorous pedoturbation.

The OC contents in HA are generally high and decrease with depth in profile 1, whereas they slightly increase with depth in profile 2. The OC contents in FA of profile 1 follow a similar decreasing trend with depth, whereas they fluctuate in profile 2, as likely effect of a more active soil free of tree root influence. The high amount of Ca throughout the profile, despite the very low amounts of carbonates, indicates the higher and long standing weathering conditions of the terra rossa soil. The long polycyclic pedogenic evolution of the soil is actually documented by micromorphological features, generally more preserved in profile 2, including carbonate fragments with micritic calcite infills (evidence for decalcification and re-carcification processes) and iron nodules (indicating earlier profile development under more humid conditions). For brevity, these are not discussed in the below section.

3.3. Micromorphology

3.3.1. Microstructure and porosity

Both profiles have similar microstructure (MS), and an open porphyric c/f-related distribution, characterized by rugose welded crumb intergrading to crumb structure from the Ap to the Bt horizons, particularly in profile 1.

In the Ap1 and Ap2 horizons of both profiles the MS is partly massive and partly complex (Figure 2a), but more commonly compact/massive in Ap2, with well-developed rugose welded crumb MS (Figure 2b). However, in the same horizons a granular and partially accommodated to unaccommodated moderately developed subangular blocky MS (Figure 2c) is dominant (Table 3). Common welded and blocky/wedge-like MSUs and clay aggregates were also observed in profile 2, particularly in horizons Bt1 and Bt2 (Table 3), despite the more intense faunal activity in this profile. In horizons Bt1 and Bt2, particularly in profile 1, the MS is generally less massive and complex, with rugose welded crumb, granular and partially to well-accommodated subangular blocky MSUs.

These most likely reflect the loosening process that might be expected to occur via the action of the tree fine roots enlarging existing pores and crack systems (Gibbs and Reid, 1988; Clemente et al., 2005). The loosening process is also indicated by the increasing variety of pores and higher porosity (Table 4). All the horizons are moderately to very porous according to Pagliai and Vignozzi (2002). On average the total microporosity varies

Table 2. Physical and chemical properties of the studied profiles. Profile 1: under canopy. Profile 2: between the trees. n.d. = not detectable.

		Profile 1				Profile 2			
		Ap1	Ap2	Bt1	Bt2	Ap1	Ap2	Bt1	Bt2
Lower boundary (cm)		10	20	49	80/85	10	30	50	80/95
Rock fragments (>2 mm)	(g kg^{-1})	96	4	4	0	92	21	0	2
Very coarse sand (2–1 mm)	(g kg^{-1})	13	12	13	10	15	13	8	9
Coarse sand (1–0.5 mm)	(g kg^{-1})	19	24	18	20	20	31	20	18
Medium sand (0.5–0.25 mm)	(g kg^{-1})	58	65	55	61	62	70	62	61
Fine sand (0.25–0.02 mm)	(g kg^{-1})	331	293	304	282	351	293	305	307
Total sand	(g kg^{-1})	421	394	390	373	448	407	395	395
Silt (0.02–0.002 mm)	(g kg^{-1})	356	288	268	257	354	295	288	254
Clay (<0.002 mm)	(g kg^{-1})	223	318	342	370	198	298	317	351
pH (H_2O)		7.1	7.1	7.7	7.9	7.1	7.1	7.5	8.0
pH (KCl)		6.9	6.8	6.5	6.5	7.1	7.1	6.8	6.7
$CaCO_3$ tot	(g kg^{-1})	4	n.d.	n.d.	n.d.	12	8	n.d.	n.d.
OC	(g kg^{-1})	47	41	12	11	44	30	17	9
N tot	(g kg^{-1})	2.2	1.8	1.0	1.0	2.3	1.8	1.2	1.0
C/N		21	23	12	11	19	17	14	9
P_2O_5	(g kg^{-1})	20	5	3	3	17	4	5	4
Ca^{++}	(cmol kg^{-1})	23.39	22.30	20.27	20.27	25.50	24.17	21.83	19.80
Mg^{++}	(cmol kg^{-1})	1.80	1.54	1.29	1.29	1.29	1.03	1.03	1.03
Na^+	(cmol kg^{-1})	0.54	0.49	0.60	0.65	0.27	0.33	0.49	0.22
K^+	(cmol kg^{-1})	0.74	0.48	0.29	0.13	0.58	0.45	0.16	0.06
Sum of exch. cations	(cmol kg^{-1})	26.47	24.81	22.45	22.34	27.64	25.98	23.51	21.11
CEC	(cmol kg^{-1})	26.69	24.97	22.60	22.60	27.65	26.10	23.78	21.32
BS	(%)	99	99	99	99	100	100	99	99
Exch. acidity	(cmol kg^{-1})	0.23	0.19	0.15	0.26	0.06	0.12	0.29	0.19
HA	(g kg^{-1})	5.35	2.45	2.23	0.30	0.26	0.26	0.20	0.10
FA	(g kg^{-1})	31.26	12.85	23.70	30.70	23.70	26.85	28.60	25.12
OC in HA	(g kg^{-1})	461.50	413.50	240.00	166.00	370.50	355.00	406.00	414.00
OC in FA	(g kg^{-1})	15.50	20.00	7.50	1.50	8.50	13.00	1.50	10.50
HA OC in total sample	(g kg^{-1})	2.47	1.01	0.54	0.05	0.10	0.09	0.08	0.04
FA OC in total sample	(g kg^{-1})	0.48	0.26	0.18	0.05	0.20	0.35	0.04	0.26

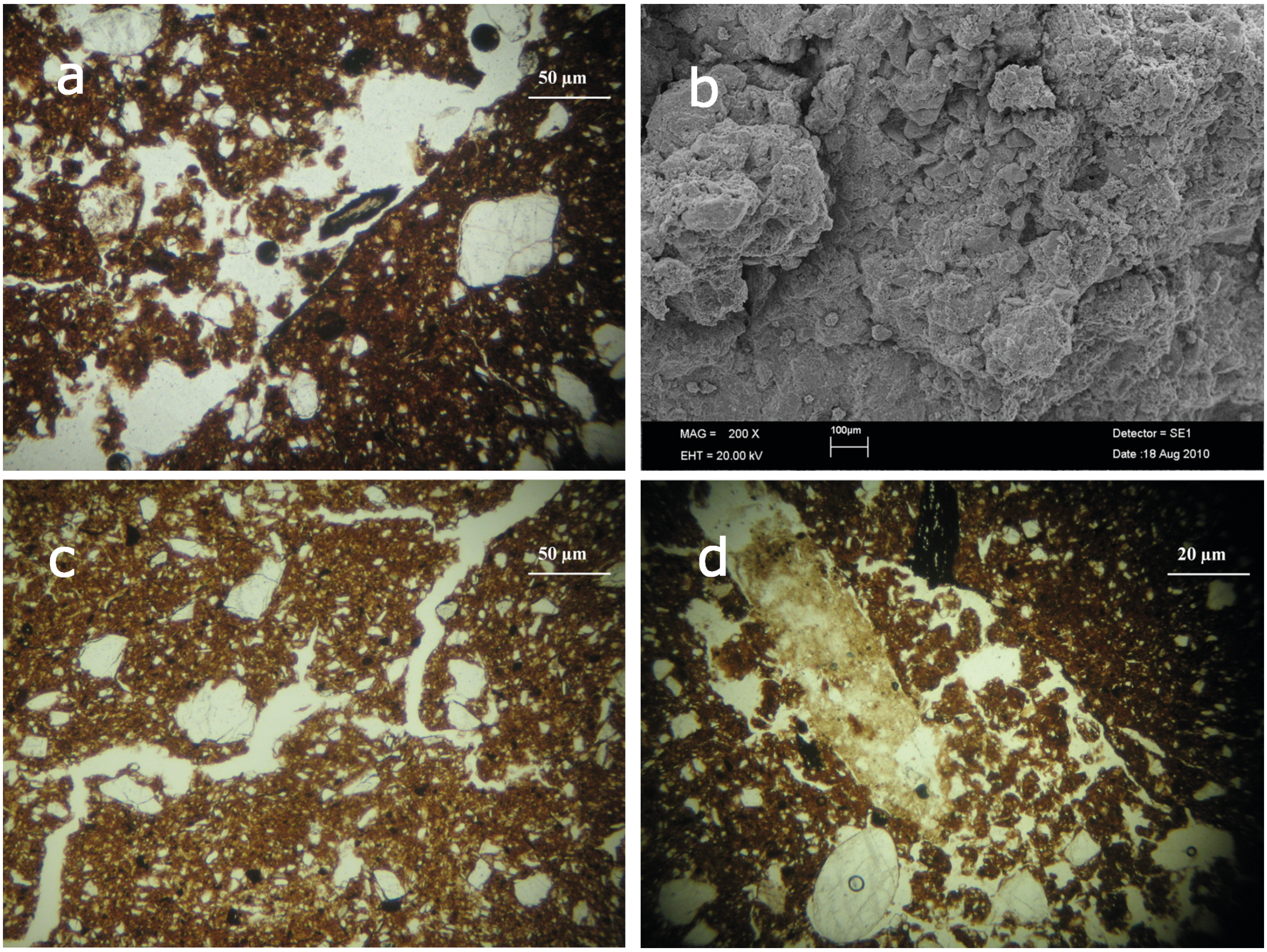

Figure 2. a) Profile 1, Ap1 h. Massive and crumb structure in matrix (PPL, 1 cm: 50 µm). b) Profile 1, Ap2 h. Well-developed welded MSU. SEM. c) Profile 2, Ap2 h. Unaccomodated moderately developed subangular blocky MS (PPL). d) Profile 1, Bt1 h. Faunal excrements infill and root remnant (PPL).

Table 3. Microstructure of profiles 1 and 2. A = Well-developed- welded rugose. B = Well-developed- welded rugose to granular – crumb. C = Granular-partially accommodated to unaccomodated moderately developed subangular blocky. D = Well-developed blocky wedge-like/clay aggregates. E1 = CBS-MSUs incomplete to rounded/oval concentrated striated b-fabric. E2 = CBS-MSUs with grano- and mono- striated with stripple speckled b-fabric.

	Horizon	A	B	C	D	E1	E2
Profile 1	Ap1	Frequent		Dominant		Occasional	
	Ap2	Frequent	Frequent	Dominant		Occasional	
	Bt1		Common	Frequent		Frequent	Frequent
	Bt2		Common	Frequent		Frequent	Frequent
Profile 2	Ap1	Frequent		Dominant		Occasional	
	Ap2	Frequent	Frequent	Dominant		Occasional	
	Bt1				Common	Frequent	
	Bt2				Common	Rare	Rare

Table 4. Pore types and pore size (m^{-6}) in profiles 1 and 2. In each horizon interconnected pore types are marked by the same upper case letter (pores types marked as "AB" are interconnected with both "A" and "B" pores).

	Horizon	Channels	Chambers	Planes	Star-shaped vughs	Regular vughs	Voids
Profile 1	Ap1	500–1000 (abundant)	100–500	50–500		50–100	
	Ap2	100–250 (frequent)	100–250 (frequent)			50–100 (A)	250–500 (abundant) (A)
	Bt1	100–250 (frequent) (A)	100–500 (abundant) (ABC)	100–500 (frequent) (B)	50–100 (abundant) (C)		
	Bt2	100–250 (abundant)	100–500 (abundant)	100–500 (abundant)	50–100 (abundant)		
Profile 2	Ap1		100–500 (A)	50–100 (B)	50–100 (abundant) (AB)		
	Ap2		100–500 (A)	50–100 (B)	50–100 (abundant) (AB)		
	Bt1	100–250 (abundant) (AB)	100–250 (abundant) (A)	100–200 (abundant) (B)			
	Bt2		100–500 (abundant) (A)			50–100 (abundant) (A)	

from 20% in the surface horizons of profile 1 and in all horizons in profile 2 to 30% in the Bt1 and Bt2 horizons of profile 1. Interconnected voids (chambers, channels, planes, and regular vughs) of medium size (100 to 500 µm) are common in the surface horizons (Table 4). The increasing channels, planes, and star-shaped vughs, together with the 50% increase in the total microporosity in the Bt horizons of profile 1, are most likely related to the loosening action of the roots, along with faunal activity (Kooistra and Pulleman, 2010). The increased distribution of the channels and planes is instead most likely connected to the shrink–swell processes discussed below.

Apart from the macroscopic compaction layer observed in profile 1 (horizon A2), no systematic increase in bulk density and/or decrease in porosity was observed in the soil adjacent to the roots. This is in disagreement with the model proposed by Dexter (1987) and with some other studies (e.g., Ryan and McGarity, 1983; Guidi et al., 1985; Braunack and Freebairn, 1988; Liddell, 1992; Bruand et al., 1996). It is worth mentioning that Young (1998) remarked that many previous studies were based on sieved soil samples and their applicability to real field conditions was questionable.

3.3.2. Shrink–swell and CSB features

Shrink–swell features are common in both profiles, as indicated by the abundant stress-oriented clay domains (Figure 3; Table 3). However, they are relatively rare in the Bt2 of profile 2, most likely because were degraded by the particularly abundant faunal activity. The stress features are more pronounced and common in the Bt1 horizons of the two profiles and in the Bt2 of profile 1. The enmeshing and anchoring action of the roots does not seem to have reduced the intensity of the shrink–swell phenomenon, in contrast with what was suggested by Mitchell and van Genuchten (1992). Incomplete to rounded/oval concentrated striated b-fabric (CSB) MSUs are present in all the horizons, but less common in the Ap horizons (Figures 3a–3d). In the Bt horizons the CSB MSUs have been developed by abundant grano- and monostriated b-fabric forming faces of the MSUs together with stipple speckled b-fabric (Bullock et al., 1985) in red to reddish brown (2.5 YR3/4) composite colored matrix in frequent areas. These areas possibly indicate the mixed/incorporated presence of the earlier and recent stress phenomena in parts of the matrix. The CSB MSUs are more prominent and frequent in the Bt2 horizon of profile 1.

The abundant faunal activity in the Bt2 horizon of profile 2 may have inhibited the formation of the CSB MSUs in this horizon (Table 3). Rare broken limpid clay coatings are present in the groundmass, along cracks, and void infills of both Bt2 horizons, and in the Ap1 and Bt1 horizons of profile 2, providing additional indications for the intense faunal activity and the shrink–swell processes.

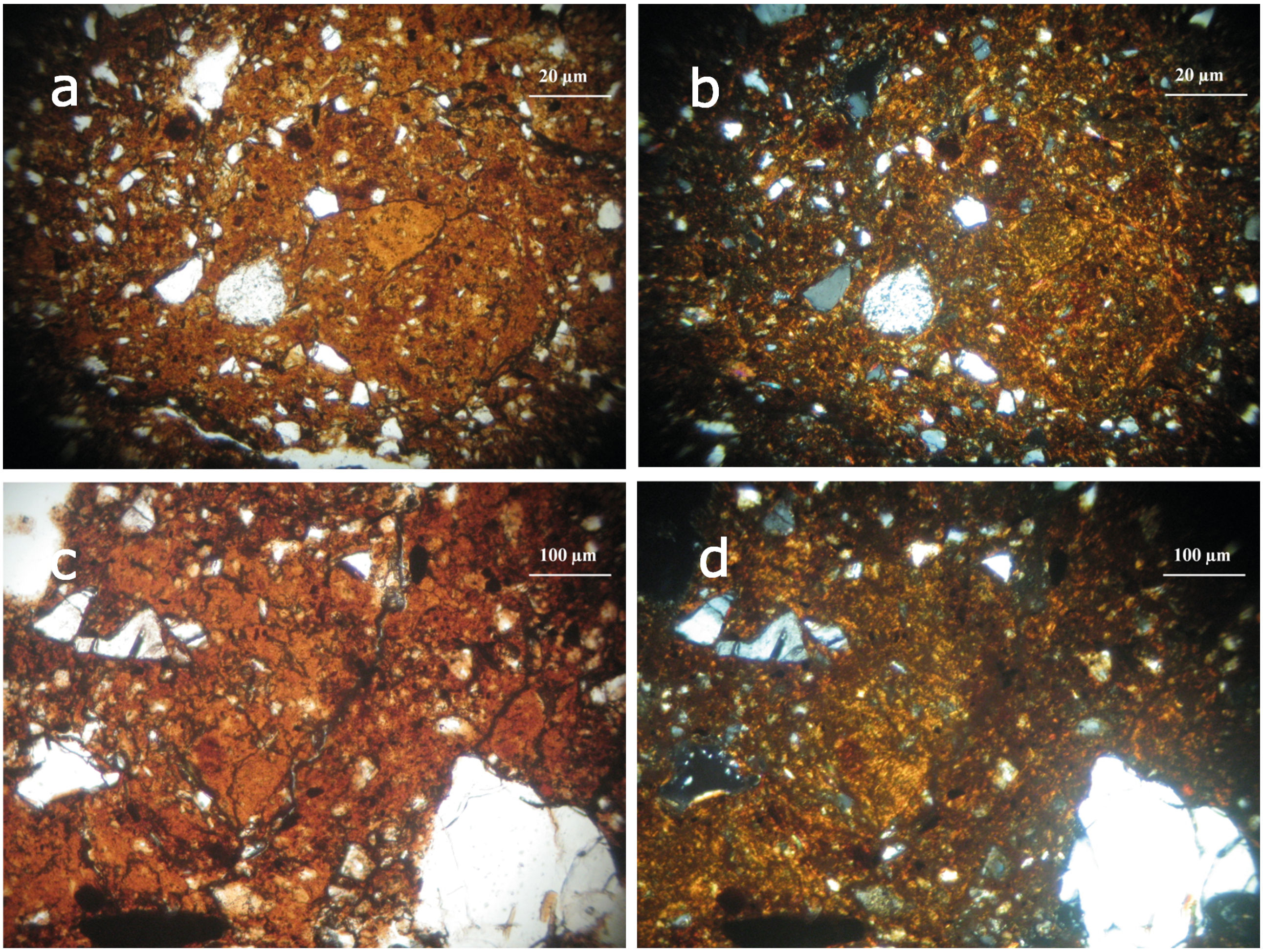

Figure 3. a) Profile 1, Ap2 h. CSB (concentrated striated b-fabric) MSU, in PPL. b) same as (a), in XPL. c) Profile 2, Bt1 h. Welded CSB (concentrated striated b-fabric) MSU in clayey matrix, in PPL. d) same as (c), in XPL.

In disagreement with Dorioz et al. (1993) and Clemente et al. (2005), no clear micromorphological evidence of clay reorganization was observed around the roots at the root–soil interface, although this mechanism may have contributed to generate the oriented clay domains. This is most likely due to the development of roots taking place along the main pre-existing pores and cracks in a highly porous soil ecosystem rich in biological activity.

3.3.3. Bioturbation

The faunal activity is frequent and vigorous in both profiles. Earthworm channels and casts are frequent in all the horizons, with channel/pore infills of smaller earthworm and arthropod excrements/pellets (Figure 2d). Reworked and decomposed organic residues are more common in the Ap horizons, whereas decomposed and humified residues are more frequent in the Bt horizons. In Ap1 of profile 1 some MSUs/aggregates consist of plant residues and oriented clay domains (Figure 4a). Worm casts in the Ap horizons are massive/angular to subangular blocky. The smaller earthworms and/or arthropods may have induced the formation of the common rounded and the welded porous crumb MSUs (Figure 4b) within the b-fabric of the surface horizons. Frequent rounded MSUs (100–500 µm) that probably formed as large faunal excrements are also present in the Bt horizons, highlighting the earthworm role with regard to both macro- and microaggregate formation, in agreement with Shipitalo and Le Bayon (2004). On the other hand, no evidence of clay orientation was observed within worm casts, in disagreement with Marinissen et al. (1996). Decomposed fine roots coated by repeated clay size material with networks of organic filaments (Figure 4c) and roots intergrading with clay aggregates/crumb MSU (Figure 4d) were also observed, particularly in profile 2 as an additional indicator of a more biologically active soil.

3.4. Clay minerals

The same dominant clay minerals were observed in both profiles. Only the diffractograms obtained for horizons Ap1 and Bt1 of profile 2 are shown in Figure 5. Illite (8.8–

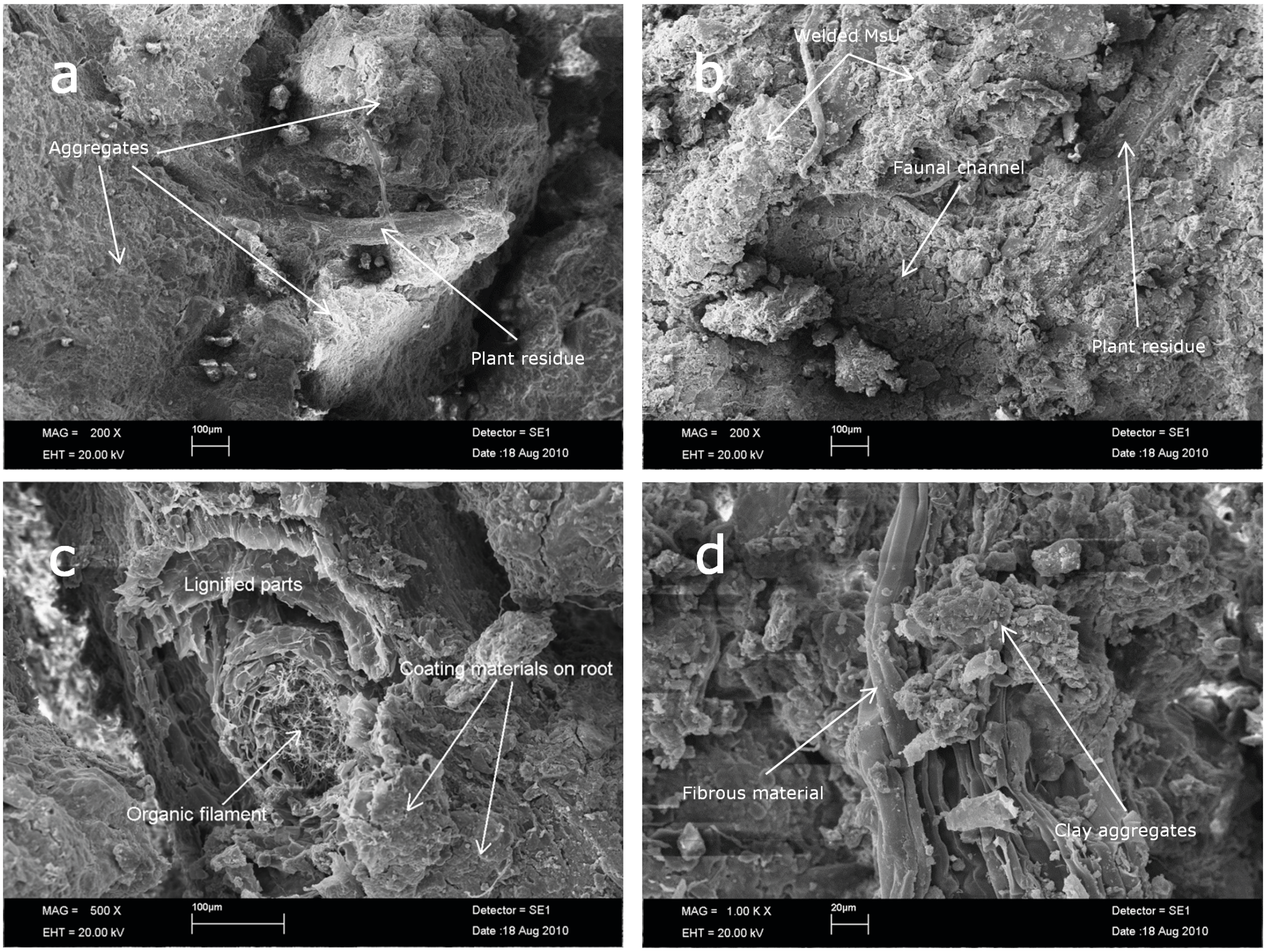

Figure 4. a) Profile 1, Ap1 h. Plant residues and shrink–swell oriented aggregates. SEM. b) Profile 2, Ap1 h. Faunal channel and plant residues in welded crumb MSU. SEM. c) Profile 2, Ap2 h. Welded aggregate with clay material on decomposed fine root, and organic filament infill. SEM. d) Profile 2, Bt1 h. Decomposed root materials intergrading with welded MSU; fibrous material and clay aggregates. SEM.

8.9 2-Θ, or around 10.2 Å) is the dominant clay mineral, followed by kaolinite (12.3–12.4 2-Θ, or around 7.2 Å), chlorite (6.1–6.2 2-Θ, or around 14.5 Å), and by traces of smectite in horizons Ap1 (2-Θ or around 16.5 Å at Mg saturation) and Bt1 (2-Θ, or around 18 Å: at Mg saturation and glycerol solvation). The dominance of illite and the almost total absence of smectite do not tie well with the abundant shrink–swell features observed in both profiles. This may be connected to both a long enduring formation of a matured soil overlying the Miocene parent material and a long period of olive cultivation. These are most likely the two processes that, at very different time scales, can both contribute to the transformation of smectite to illite.

In pedogenic terms the absence of a C horizon in both profiles is most likely an indicator for the enduring formation of these soils throughout the geological time. Bourbia et al. (2013) observed that the olive roots systematically enrich K in the rhizosphere soil inducing transformation of smectite to illite and/or to illite-like layers.

Earlier studies documented that soil–plant potassium transfers can even have short-term impact on the clay minerals, inducing the formation of "illite-like" layers in the top soil/root zone (Barré et al., 2007a, 2007b, 2009). More in general, the root action can affect the weathering rates of clay minerals by depleting or concentrating the cations in the rhizosphere (April and Keller, 1990; Hinsinger and Jaillard, 1993; Paris et al., 1995). The amount of exchangeable K in the surface horizon of profile 1 is actually higher than in that of profile 2, most likely as a consequence of both root activity and fruit fall.

4. Main findings

Sharper vertical gradients in organic matter contents (particularly OC, HA, and OC in HA) were determined in

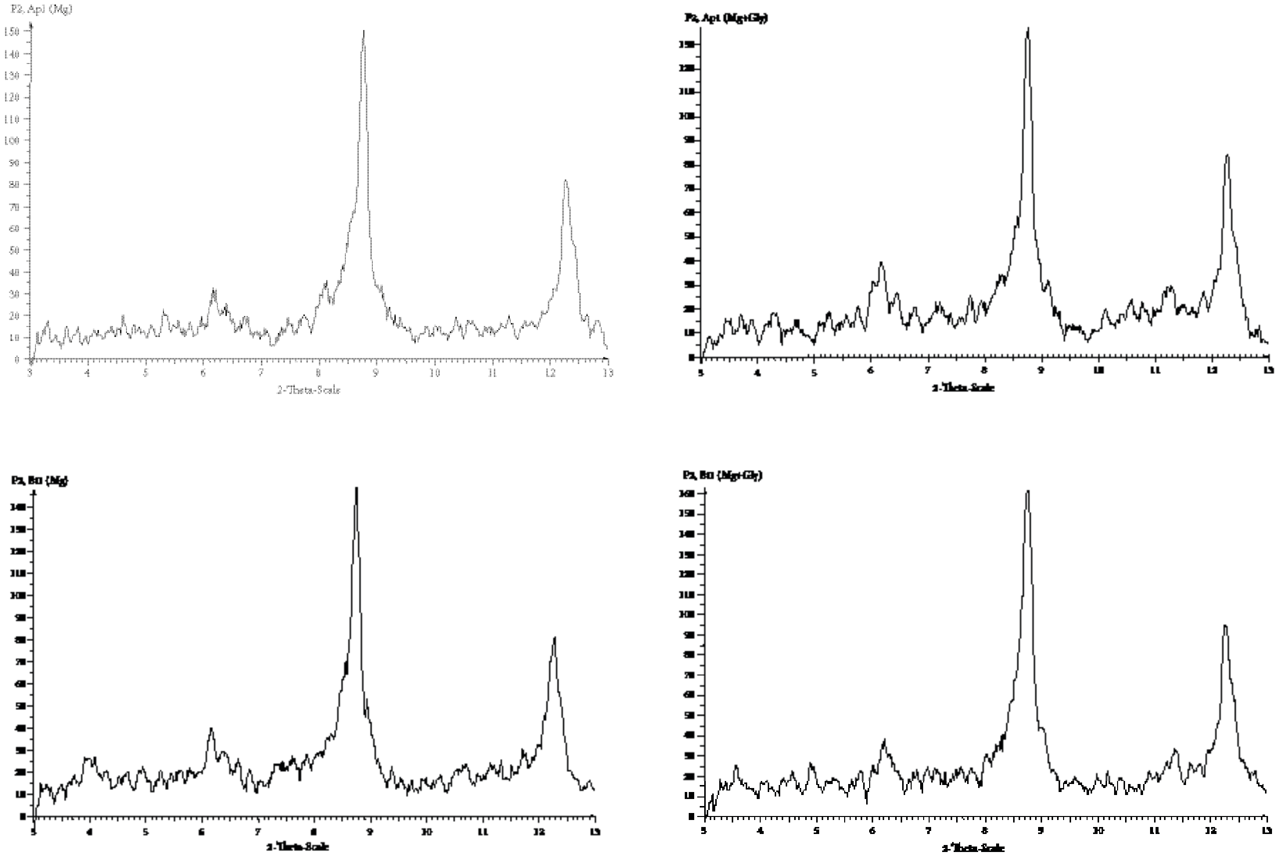

Figure 5. The X-ray diffraction patterns of the clay minerals for profile 2. Glycolated (Mg + Gly) and Mg++ (Mg) saturated slides. a) Ap1 (Mg); b) Ap1 (Mg+Gly); c) Bt1 (Mg); d) Bt1 (Mg+Gly).

profile 1 (under the tree) compared to profile 2, indicating the combined effect of the higher litter input under the tree and of a less active soil under tree root influence.

Macroscopically, a relative soil compaction in the lower topsoil (Ap2) was observed under the tree compared to the Ap1 and to the underlying Bt horizons, in connection to the pressure of the anchoring roots. With regards to the Bt horizons, less compaction and higher porosity were instead observed in profile 1 compared to profile 2, indicating the loosening action of the deeper olive roots under the tree. The highest degree of bioturbation, due to the action of the roots and of the bigger earthworms (up to 1 cm wide) was described in the topsoil (Ap1) of profile 1, around the trunk and between and below the main roots. However, the deeper horizons of profile 2 showed the highest overall faunal activity most likely by a more complex community of smaller earthworms and arthropods.

Microscopically, the two profiles showed similar microstructure and stress features, as an evidence of their common origin and development, with some relevant differences. Profile 2 showed more evidence of stability and maturation. In the Bt horizons, well-developed blocky wedge-like aggregates could be observed only in profile 2. In profile 1, the frequent crumb or moderately developed subangular blocky MS, associated with different pore types and with an overall 50% increase in total microporosity, are the most likely indicators of the loosening action of the olive roots. No evidence of clay reorganization or reduced porosity was observed around the roots at the root–soil interface, most likely due to the development of roots taking place along the main pre-existing pores and cracks, in a highly porous soil.

Stress features and CSB MSUs were more common and prominent in the Bt horizons, particularly in profile 1. They were less preserved, however, in the Bt2 horizon of profile 2 where the highest biological activity was observed, which can inhibit the formation of these features or degrade them. Only traces of smectite were determined as a possible indicator of past shrink–swell processes. The dominance of illite-like clay minerals in all horizons of both profiles, apparently inconsistent with the observed abundant stress features, might be explained by the transformation of smectite induced by the long enduring maturation of the soil and by the long-lasting K-enriching action of the olive roots and litter.

It is challenging to distinguish inherited from tree-induced morphological features working in the field, where many independent pedogenic processes take place at different time scales at the tree rhizospheres and at the top soils between trees. In this study we applied indicators at different scales to base the evaluation on the integration of multidisciplinary information. Another difficulty was linked to the substantial lack of similar studies available for comparative interpretation. Most of the previous studies on the relationships between soil and tree roots development were either only very focused on specific soil properties or conducted in laboratory conditions. They most often did not integrate different types of information by adopting a pedogenesis perspective, and were site-specific and based on low numbers of samples. Furthermore, none of them targeted the olive–terra rossa agro-ecosystem. It is not surprising that some of our findings are in contrast with previous results. Our results indicate that several research questions are open and that there is a need for more systematic, integrated, and comparative research on this subject.

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References

April R, Keller D (1990). Mineralogy of the rhizosphere in forest soils of the eastern United States. Biogeochemistry 9: 1-18.

Barbera G, Dettori S (2006). Traditional olive groves in the Mediterranean cultural landscapes: history, functions, future. In Caruso T, Motisi A, Sebastiani L, editors. Proceedings of the 2nd International Seminar on Recent Advances in Olive Industry "OliveBioteq 2006".

Barré P, Berger G, Velde B (2009). How element translocation by plants may stabilize illitic clays in the surface of temperate soils. Geoderma 151: 22-30.

Barré P, Velde B, Abbadie L (2007a). Dynamic role of "illite-like" clay minerals in temperate soils: facts and hypothesis. Biogeochemistry 82: 77-88.

Barré P, Velde B, Catel N, Abbadie L (2007b). Soil–plant potassium transfer: impact of plant activity on clay minerals as seen from X-ray diffraction. Plant Soil 292: 137-146.

Blevins RL, Holowaychuk N, Wilding LP (1970). Micromorphology of soil fabric at tree root-soil interface. Soil Sci Soc Am J 34: 460-465.

Bourbia SM, Barré P, Naït Kaci MB, Derridj A, Velde B (2013). Potassium status in bulk and rhizospheric soils of olive groves in North Algeria. Geoderma 197-198: 161-168.

Braunack MVA, Freebairn DM (1988). The effect of bulk density on root growth. In Witney BD, Spoor G, Soane BD, Douglas JT, editors. Proceedings of the 11th International Conference of the International Soil Tillage Research Organisation, on Tillage in traffic and crop production. Edinburgh. Vol. I, pp. 25-30.

Bruand A, Cousin I, Nicoullaud B, Duval O, Bégon JC (1996). Backscattered electron scanning images of soil porosity for analyzing soil compaction around roots. Soil Sci Soc Am J 60: 895-901.

Bullock P, Federoff N, Longerius A, Stoops G, Tursina T, Babel U (1985). Handbook for soil thin section description. Wolverhampton, UK: Waine Research Publication.

Carter MR, Angers DA, Kunelius HT (1994). Soil structural form and stability, and organic matter under cool-season perennial grasses. Soil Sci Soc Am J 58: 1194-1199.

Clemente EP, Schaefer CEGR, Novais RF, Viana JH, Barros NF (2005). Soil compaction around *Eucalyptus grandis* roots: a micromorphological study. Soil Research 43: 139-146.

Daget P (1977). Le Bioclimat Mediterraneen: Analyse des formes climatiques par le système d'Emberger. Vegetatio 34: 87-103 (in French).

Dexter AR (1987). Compression of soil around roots. Plant Soil 97: 401-406.

Dichio B, Romano M, Nuzzo V, Xiloyoannis C (2002). Soil water availability and relationships between canopy and roots in young olive trees (cv Coratina). Acta Hortic 586: 255-258.

Dorioz JM, Robert M, Chenu C (1993). The role of roots, fungi and bacteria on clay particle organization. An experimental approach. Geoderma 56: 179-194.

FAO (2006). Guidelines for soil description. Fourth edition. Rome, Italy: FAO.

Fernandez JE, Moreno F, Cabrera F, Arrue JL, Martín-Aranda R (1991). Drip irrigation, soil characteristics and the root distribution and root activity of olive tree. Plant Soil 133: 239-251.

Gibbs RJ, Reid JB (1988). A conceptual model of changes in soil structure under different cropping systems. Adv Soil S 8: 123-149.

Gregory PJ (2006). Plant Roots. Growth, Activity and Interaction with Soils. Oxford, UK: Blackwell Publishing.

Guidi G, Poggio G, Petruzzelli G (1985). The porosity of soil aggregates from bulk soil and from soil adhering to roots. Plant Soil 87: 311-314.

Hinsinger P, Jaillard B (1993). Root-induced release of interlayer potassium and vermiculitization of phlogopite as related to potassium depletion in the rhizosphere of ryegrass. J Soil Sci 44: 525-534.

IUSS Working Group WRB (2015). World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. Update 2015. World Soil Resources Reports No. 106. Rome: FAO.

Kodešová R, Kodeš V, Žigová A, Šimůnek J (2006). Impact of plant roots and soil organisms on soil micromorphology and hydraulic properties. Biologia 61: 339-343.

Kooistra MJ, Pulleman MM (2010). Features Related to Faunal Activity. In Stoops G, Marcelino V, Mees F, editors. Interpretation of Micromorphological Features of Soils and Regoliths. Amsterdam, Netherlands: Elsevier. pp. 397-418.

Krebs M, Kretzschmar A, Chadœuf J, Goulard M (1993). Investigations on distribution patterns in soils: basic and relative distributions of roots, channels and cracks. Dev Soil Sci 22: 437-449.

Liddell CM (1992). Experimental approach to measure the compression of soil around emerging coleoptiles. Soil Biol Biochem 24: 471-477.

Loumou A, Giourga C (2003). Olive groves: the life and identity of the Mediterranean. Agric Human Values 20: 87-95.

Marinissen JCY, Nijhuis E, van Breemen N (1996). Clay dispersability in moist earthworm casts of different soils. Appl Soil Ecol 4: 83-92.

Materechera SA, Dexter AR, Alston AM (1992). Formation of aggregates by plant roots in homogenised soils. Plant Soil 142: 69-79.

Materechera SA, Kirby JM, Alston AM, Dexter AR (1994). Modification of soil aggregation by watering regime and roots growing through beds of large aggregates. Plant Soil 160: 57-66.

Miller RM, Jastrow JD (1990). Hierarchy of root and mycorrhizal fungal interactions with soil aggregation. Soil Biol Biochem 5: 579-584.

Misra RK, Dexter AR, Alston AM (1986). Maximum axial and radial growth pressures of plant roots. Plant Soil 95: 315-326.

Mitchell AR, van Genuchten MT (1992). Shrinkage of bare and cultivated soil. Soil Sci Soc Am J 56: 1036-1042.

Nergiz C, Engez Y (2000). Compositional variation of olive fruit during ripening. Food Chem 69: 55-59.

Pagliai M, Vignozzi N (2002). The soil pore system as an indicator of soil quality. In: Pagliai M, Jones R, editors. Sustainable land management-environmental protection. A soil physical approach: Advances in Geoecology 35. Reiskirchen, Germany: Catena Verlag, pp. 71-82.

Paris F, Bonnaud P, Ranger J, Robert M, Lapeyrie F (1995). Weathering of ammonium- or calcium-saturated 2:1 phyllosilicates by ectomycorrhizal fungi in vitro. Soil Biol Biochem 27: 1237-1244.

Reid JB, Goss MJ (1982). Interactions between soil drying due to plant water use and decrease in aggregate stability caused by maize roots. J Soil Sci 33: 47-53.

Ryan PJ, McGarity JW (1983). The nature and spatial variability of soil properties adjacent to large forest eucalypts. Soil Sci Soc Am J 47: 286-293.

Shipitalo MJ, Le Bayon RC (2004). Quantifying the effects of earthworms on soil aggregation and porosity. Earthworm Ecology 10: 183-200.

Six J, Bossuyt H, Degryze S, Denef K (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil Till Res 79: 7-31.

Società Italiana della Scienza del Suolo (1997). Metodi di analisi fisica del suolo. Milan, Italy: Franco Angeli.

Società Italiana della Scienza del Suolo (2000). Metodi di analisi chimica del suolo. Milan, Italy: Franco Angeli.

Stoops G (2003). Guidelines for analysis and description of soil and regolith thin sections. Madison, WI, USA: Soil Science Society of America.

Tisdall JM, Oades JM (1982). Organic-matter and water-stable aggregates in soils. J Soil Sci 33: 141-163.

Young IM (1998). Biophysical interactions at the root-soil interface: a review. J Agr Sci 130: 1-7.