Soil ecosystem functions in a high-density olive orchard managed by different soil conservation practices

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Abstract

The long-term effects of two different soil management practices, natural grass cover (NC) and conservation tillage (CT), on soil functions (carbon sequestration, habitat for organisms, and water movement and retention) were determined in a high-density, mature olive orchard (*Olea europaea* L. cv. Frantoio) growing in a sandy loam soil (Typic Haploxeralf) in a Mediterranean environment. Ten years after the beginning of the different soil management, soil samples were collected at 0-10 and 10-20 cm depth and at two distances from the trunk, underneath the olive canopy (UC) and in the inter-row (IR). There were no differences in fruit yield, oil yield, and yield efficiency between the two soil management systems during the 2011-2013 period. CT negatively affected soil organic carbon pools (total and humified), but only at the IR position. The distance from the plant did not significantly influence soil structure and hydrological properties, while NC treatment increased water movement and retention. Tillage reduced the microarthropod diversity, namely Collembola and 'Other arthropods', which were the most sensitive groups to soil perturbation. We conclude that natural grass cover was more effective than conservation tillage in maintaining or improving elements of soil functionality.

Keywords: carbon sequestration, *Olea europaea* L., soil functions, soil management, soil microarthropods, soil structure

1. Introduction

The soil is a key component of terrestrial ecosystems. Its foremost functions involved in agro-ecosystem services include biomass production, storage and transformation of nutrients and organic compounds, storage and filtration of water, regulation of water fluxes, source of genetic biodiversity, storage and cycling of carbon (Ritz and Van der Putten, 2012). Therefore, sustainable agriculture should be able to manage the soil to satisfy productivity needs while preserving or enhancing soil quality.

Olive groves are widespread in the Mediterranean basin due to their adaptability to soil and environmental constraints. The most common soil management practice in olive orchards is still conventional tillage by shallow mouldboard ploughing or harrowing. Conventional tillage allows to reduce soil water evaporation, increase surface roughness and limit weed development, thus alleviating root limitations caused by competition for water and mineral nutrients (Palese et al., 2014). These limitations can be particularly relevant in high- and very high-density olive orchards (Metzidakis et al., 2008; Simoes et al., 2014).

However, conventional tillage has become a major threat to soil quality, as a result of a number of undesirable effects on soil physical, chemical and biological properties (Pagliai et al., 2004; Wardle et al., 2004; Álvaro-Fuentes et al., 2007). Depending on the tillage technique, the effects of long-term tillage practices may vary in magnitude. These effects often include poor soil aggregation, reduced porosity and/or excessive proportion of large macropores (fissures) with respect to micropores, poor water retention and depletion of soil organic carbon. Increased risk of soil erosion, higher soil susceptibility to compaction or crusting, decrease of soil biological activity and diversity, less water and nutrients available for roots, and higher CO_2 emission into the atmosphere have been documented in soils subjected to tillage practices (Lal and Kimble, 1997; Marquez-García et al., 2013; Ussiri and Lal, 2009).

It is generally accepted that soil organic matter plays a significant role in soil agroecosystem services, and that tillage-induced changes in soil physical, chemical and biological traits are, to a large extent, a consequence of changes in the amount and composition of soil organic matter. The latter consists of a wide array of chemically and functionally different pools, ranging from more labile compounds with fast-medium turnover (microbial cells, plant and animal residues, products of the activity and decay of microorganism cells, root exudates etc.), to more recalcitrant compounds with slow turnover (humic substances and other compounds chemically resistant to biological decomposition, such as lignin, suberin, resins, fats and waxes) (Rovira and Vallejo, 2007).

Conservation tillage is recommended by EU guidelines for sustainable land management as a method of soil cultivation to contrast soil physical degradation and organic carbon depletion, together with complementary practices enabling a higher supply of organic matter to the soil. The basic principle of conservation tillage is to minimize soil physical disturbance by means of mechanical operations that exclude soil inversion and allow a higher retention of crop residues at the soil surface (Lal and Kimble, 1997). Less soil disturbance also means a better protection of soil structure, which promotes organic carbon sequestration and stabilization within soil aggregates. Many studies dealing with a wide range of crops, soil types and environmental conditions, have shown that no-tillage and minimum tillage effectively increase organic carbon storage and create better soil conditions in the upper soil layers than conventional tillage (Madejon et al., 2009; Prasad et al., 2016; Ussiri and Lal, 2009).

The use of natural vegetation or selected crops in the orchard inter-row has shown a great potential for C sequestration and improvement of soil fertility (Castro et al., 2008; Gómez et al., 2009; Moreno et al., 2009; Ramos et al., 2010). This practice is beneficial because it increases organic carbon content by a variable amount of residues, which stimulate biological activity and diversity, and enhance plant nutrient availability. Moreover, ground-covering vegetation absorbs rainwater energy, thus protecting the soil surface from aggregate disruption, crusting and erosion, and helps reduce soil compaction caused by machinery traffic (Pardini et al., 2002; Gucci et al., 2012).

Nevertheless, olive growers are often concerned that cover cropping can cause yield reductions due to competition for soil water and nutrients, especially in rainfed orchards. Competition may be particularly detrimental under spontaneous grass cover, which tends to grow fast in spring during the critical stages of the olive phenological cycle. In this regard, however, the effects of cover crops can be different depending on a number of environmental and management factors and their complex interactions (Pardini et al., 2002). Gucci et al. (2012) reported that a permanent natural cover, as compared to tillage-based management, led to a reduction in fruit and oil yield when established too early in a young olive grove. Gómez (2005) suggested to avoid the establishment of cover crops in early spring in order to prevent water competition and severe yield penalty. However, under grass cover less competition for nutrients can be achieved by repeated grass mowing and improved soil water storage capacity (Palese et al., 2014).

The evaluation of soil management effectiveness and sustainability needs a case-by-case approach that takes into account the site-specificity of land degradation risk. Furthermore, it requires the monitoring of suitable indicators of soil quality. The latter are commonly based on soil chemical, physical and biological properties that are directly related to soil ecosystem functions and highly responsive to soil disturbance, such as soil organic matter and its fractions, soil aggregate stability, soil porosity, soil biological activity and diversity (Bünemann et al., 2018).

Bioindication is a valuable tool that permits to assess the state of conservation of an ecosystem based on the living organisms that it contains (Burel et al., 2004; Jerez-Valle et al., 2014). Some microarthropod groups are very sensitive to soil perturbation and, therefore, they are drawing more and more attention as bioindicators for soil quality assessment (Brussaard, 1997; Parisi et al., 2005; Culliney, 2013). Soil microarthropods as biological regulators (European Communities, 2010) are reported to provide a significant contribution to soil formation, soil organic matter transformation, nutrient cycling and to be involved in a wide range of interactions with micro-organisms and other invertebrates.

Orchards typically exhibit a high spatial variability in soil properties, which can be caused not only by inherent soil variability, but also by an "individual plant effect" (Zinke, 1962). In fact, every plant species leaves its signature in the underlying soil, generating a fine scale spatial variation that drives ecological processes. In general, the plant effect is stronger on chemical and biological soil properties rather than physical ones (Waring et al., 2015). This variability should be therefore investigated and characterized for a better use of soil properties as soil quality indicators and an effective assessment of soil C sequestration (Gómez et al., 2009).

The objective of this study was to evaluate the long-term (10 years) effects of two different soil conservation management practices (natural grass cover and conservation tillage) on soil functions in a mature, high-density olive orchard. In particular, we investigated: i) crop yield and yield efficiency; ii) soil structure and hydrological properties; iii) concentration and storage of organic carbon pools; iv) abundance and biodiversity of soil microarthropod communities.

2. Material and methods

2.1. Plant material and site description

The experiment was carried out in an olive orchard (*Olea europaea* L. cv. Frantoio) planted at a density of 513 trees ha^{-1} in April 2003 at the experimental farm of the University of Pisa, Italy (43°01'N; 10°36'E) located at Venturina (Livorno). Minimum pruning criteria were used for canopy management (Caruso et al., 2013) and pruned wood was shredded and distributed on the soil surface (VKD 170 Nobili, Bologna, Italy).

The climate of the study site is sub-humid Mediterranean (Nahal, 1981; Caruso et al., 2013). The climatic conditions were monitored over the study period using a weather station iMETOS IMT 300 (Pessl Instruments GmbH, Weiz, Austria) installed on site since May 2006. Potential evapotranspiration (ET_0), calculated according to the Penman-Monteith equation, was 840, 931 and 909 mm in 2011, 2012 and 2013, respectively. Annual precipitations were 419, 820 and 915 mm in 2011, 2012 and 2013, respectively.

All trees had been fully irrigated since planting until the 2006 growing season, when deficit irrigation was imposed using subsurface drip lines (Caruso et al., 2013). In 2011 trees received only complementary irrigation, corresponding to 33 m^3 ha^{-1}. In 2012 and 2013 trees were not irrigated from the 41^{th} to the 71^{th} and from the 60^{th} to the 85^{th} day after full bloom (DAFB), respectively, and fully-irrigated for the rest of the irrigation period. Accordingly, trees received approximately 48% and 67% of the entire water needs in 2012 and 2013, respectively.

The soil was a Typic Haploxeralf, coarse-loamy, mixed, thermic (Soil Survey Staff, 2010), 1.5 m deep, with sandy loam texture (600 g kg^{-1} sand, 150 g kg^{-1} clay and 250 g kg^{-1} silt). Within the first 0.4 m depth, it featured pH=7.9, organic matter=1.8%, cation exchange capacity=13.7 cmol[+] kg^{-1}, high Ca and Mg content, medium N, K and Na content and low P content (Gucci et al., 2012).

2.2. Soil management treatments and yield

The whole experimental soil was periodically tilled to a depth of 0.1 m until October 2004, when two different soil management strategies were started: i) conservation tillage (CT) by a power take-off-driven harrow with vertical blades (Breviglieri, Nogara, Italy), and ii) permanent natural grass cover (NC), periodically mown by a VKD 170 Nobili mulcher. Subsequently, the treatments were maintained by either tilling or grass mowing three or four times a year. Each treatment consisted of 36 trees, divided into three spatially separated plots of 12 trees each (three rows of four trees each), as reported in Gucci et al. (2012). Only the four trees of the central rows were used for vegetative measurements and fruitsampling.

Each tree was hand-harvested on 17 October 2011, 23 October 2012 and 5 November 2013 and the final yield was also expressed on the basis of the trunk cross sectional area (TCSA) to account for differences in tree size and vegetative growth. At harvest, 100 fruits per tree were randomly sampled to determine the average fruit weight. The oil content in the mesocarp was measured, after oven-drying at 70ºC, by nuclear magnetic resonance using an Oxford MQC-23 analyzer (Oxford Analytical Instruments Ltd., Oxford, UK) (Caruso et al., 2013; 2017). The oil yield of each individual tree was calculated after measuring the mesocarp oil content on a dry weight basis, the fruit fresh yield, the pulp/fruit ratio, and the ratio between the dry and fresh weight, as previously reported (Caruso et al., 2013; 2017).

In order to evaluate the effect of treatments on soil properties, in May 2014 a sampling campaign was carried out 10 years after the beginning of differential soil management. Fig. 1 shows the layout of the experimental design. In each plot, soil samples were collected from two points underneath the olive canopy (UC) and two points in the inter-row space outside the canopy projection (IR), at a distance of 0.5

and 2.50 m from the trunk, respectively. At each sampling location, disturbed and undisturbed soil samples were collected and analyzed for physical, chemical and biological properties.

2.3 Soil characterization

2.3.1 Physical properties

The soil bulk density (BD) was measured according to Blake and Hartge (1986) using the core sampling method at 0.0-0.1 m and 0.1-0.2 m depth. The contribution of skeletal and roots, whose particle density was assumed to be equal to 2.62 and 0.55 g cm^{-3} respectively, was removed.

The size distribution and water stability of soil aggregates were determined by dry and wet sieving test (Kemper and Rosenau, 1986). In both procedures, the mean weight diameter was calculated (MWD_{dry} and MWD_{wet}). From each sampling point, soil aggregates were collected down to 0.1 m depth, air dried, weighed and separated into different sized fractions (10-20, 4.75-10, 2-4.75, 1-2, <1 mm) by a vibrating sieve shaker (Retsch). The most representative size fraction was selected to perform wet sieving. Twenty g of aggregates from the most abundant size class (4.75-10 mm) were directly soaked for 5 minutes on the top of a nest of 4.75, 2, 0.25 and 0.05 mm diameter sieves immersed in water (fast wetting). The nest of sieves with its content was then vertically shaken in water by an electronic-controlled machine with a stroke of 40 mm per 10 minutes, at a rate of 30 complete oscillations per minute.

For soil structure characterization, vertically oriented thin sections (55 x 85 mm) were obtained from undisturbed soil samples collected at 0.05-0.15 m depth at each sampling point. We chose this depth in order to detect the possible occurrence of soil compaction at the lower limit of the tillage. Two images were taken for each soil thin section: one representative of the 0. 05-0.10 m depth and the other one of the 0.10-0.15 m depth. The images were analyzed using the Image-Pro Plus software (Media Cybernetics, Silver Spring, MD, USA). Total porosity and pore distribution were calculated from measurements of pore shape and size (Pagliai and Vignozzi, 2002). On the basis of their function, pores of 50-500 µm were defined as transmission pores and those greater than 500 µm as fissures (Greenland and Pereira, 1977).

Thin sections were also examined for soil structure using a Zeiss 'R POL' microscope at 25X magnification.

In order to determine soil water retention properties, 48 additional undisturbed soil samples were collected (24 at 0-0.10 m depth and 24 at 0.10-0.20 m depth). Metal cylinders of 122 cm^3 (7.2 cm diameter, 3 cm height) with a sharpened edge were used, sealed up and stored to prevent moisture loss and formation of soil structural artifacts. Soil water content at saturation was measured on sand box (Clement, 1966), whereas retention measurements at the matric potentials of -10 and -1,500 kPa were performed by means of pressure plate extractors (Klute, 1986). The moisture content at each matric potential, expressed as percentage (by weight) of the dry soil, was then converted into volume using Gardner's equation (1986).

The retention data at saturation (θ_{sat}, 0 kPa), field capacity (FC, -10 kPa) and wilting point (WP, -1,500 kPa) were used to determine the air capacity (AC=θ_{sat}-FC) and the available water capacity (AWC=FC-WP) of the soil.

2.3.2. Chemical properties

Soil total organic carbon (TOC) was determined by hot wet-oxidation with $K_2Cr_2O_7$ + H_2SO_4 (Yeomans and Bremner, 1988). Chemical fractionation of soil organic carbon was performed according to the classical procedure based on alkali extraction (0.1 M NaOH + 0.1 M $Na_4P_2O_7$) and subsequent separation of humic and non-humic organic carbon onto polyvinylpyrrolidone columns. The fractions considered were: total extractable (TEC) and humified organic carbon (HC = humic + fulvic acids). Moreover, the degree of humification (DH) was calculated as HC/TEC percent ratio (Sequi and De Nobili, 2000).

The organic C stock was calculated for each fraction with reference to an equivalent soil mass to 0.2 m depth (ESM), to account for possible differences in soil BD caused by soil management (Ellert and Bettany, 1995). We chose the mass of the 0.2 m soil layer having the lowest bulk density as reference.

For a more in-depth characterization of soil organic carbon dynamics and C sequestration potential under selected soil management practices, each size class of soil water-stable aggregates was analyzed for TOC content. Dry combustion by a CN soil analyzer was preferred to wet oxidation; the latter method would have required a larger sample size with lower organic matter samples, which would have increased inorganic interferences. TOC content in the aggregate-size fractions was expressed as g of organic carbon per kg of aggregate fraction and as g of organic carbon per kg of soil. All values are expressed on a dry weight basis.

2.3.3. Biological properties

In order to characterize soil microarthropod communities, we collected two soil cubes (1 dm^3 of soil per plant) at the two aforementioned sampling positions (UC, IR), next to the sampling points selected for the other determinations. We sampled the top soil layer only (0-10 cm) because in temperate soil ecosystems the abundance of microarthropods decreases in the deeper horizons, likely due to a lower amount of organic food resources and a reduction of the habitat complexity (Usher, 1970).

Microarthropods were extracted by Berlese-Tullgren funnels. Each sample was placed in a Berlese funnel for five days. The collected specimens were observed under a stereomicroscope and characterized as biological forms (BF) (Parisi et al., 2005).

Microarthropods were divided into three main groups (Acari, Collembola and "Other arthropods") and relative frequencies calculated. The biological soil quality was evaluated by means of the Biological Soil Quality index (BSQ_{ar}) (Parisi et al., 2005) The BSQ_{ar} index is based on the degree of adaptation of microarthropods to the soil environment as it takes into account the different biological forms of microarthropods, each classified according to an eco-morphological index (EMI) ranging from 1 (epigeic forms) to 20 (eu-edaphic forms). The sum of all EMIs from a given soil sample gives the global value of its BSQ_{ar} index. In addition, the BF biodiversity of microarthropods was determined by the following ecological indices: BF richness (S), Shannon (H'), Margalef (d).

Microarthropods were classified on the basis of their feeding morphotype diversity (Bagyaraj et al., 2016; Bellinger et al., 2018; Culliney, 2013; Krantz and Evans, 2009; Latella and Gobbi, 2008; Moore and Walter, 1998; Thyssen, 2010). All the specimens of Acari and Collembola at immature stages were not identified and were included only in the total abundance of the respective groups.

2.4. Statistical analysis

Soil data were analyzed statistically by two- or three-way ANOVA, using the StatSoft Statistica 10.0 software package (StatSoft, Tulsa, USA). In particular, the categorical factors employed were: management (M) and sampling position (P) for MWD_{dry}, MWD_{wet}, soil cumulative organic C stock and abundance of microarthropods; M, P and aggregate size (S) for TOC in aggregate fractions; M, P and sampling depth (D) for BD, macroporosity, AC, AWC, TOC, TEC HC and DH. Theoretical assumptions underlying ANOVA were checked before analysis (homogeneity of variances and normality of the distribution of residuals). Post-hoc mean separation ($p<0.05$) was performed by Duncan’s multiple range test. A one-way ANOVA was applied to highlight the combined effect of management and position on BSQar index values. Tukey’s pairwise test was used to compare significant values ($p<0.05$) and the Diversity Permutation Test to compare biodiversity indices (Hammer et al., 2001). Yield data were processed by ANOVA using a split-plot scheme, with soil treatments as main plots and years as subplots (repeated observations).

Additionally, a Principal Component Analysis (PCA) was performed to assess the relationships between soil physical and chemical properties and the abundance of microarthropods (Davis, 1986). Before performing the analysis, the variables were standardized (rescaled to have a mean of zero and a standard deviation of one). In particular, the selected properties were: abundance of Acari, Collembola, and "Other arthropods", TOC, HC, BD, MWD_{wet}, AWC, AC, regular macropores (Reg_pores) and total macroporosity (Tot_Pores). The remaining properties were excluded from the analysis because they were highly correlated with others or not significant. The first three resulting components, featuring eigenvalues greater than 1 and an overall explained variance of 86%, were retained for PCA interpretation. In order to identify the variables that were most closely correlated to each other within a single component, the following cut-off values were adopted: 0.45 (fair), 0.55 (good), 0.63 (very good) and 0.71 (excellent) (Tabachnick and Fidell, 2007).

3. Results

3.1. Yield and yield efficiency

Differences in fruit and oil yield and yield efficiency between soil management systems were not significant during the 2011-2013 period. In 2013 the fruit fresh weight of NC trees was significantly higher than that of CT ones, while in the other two years it was similar. The lowest values of yield, fruit fresh weight and mesocarp oil content were measured in 2011 under rain-fed conditions in both soil management systems (Table 1). Over the three years, the NC plots produced 7.43 and 0.96 t ha^{-1} of fruits and oil, respectively, corresponding to 91 and 106% of fruits and oil than the CT ones (Table 1). The "Year" factor was always statistically significant for all the analyzed parameters, whereas an interaction between "Year" and "Management" was observed only for fruit fresh weight (Table S1).

3.2. Soil structure and hydrological properties

Soil structure characterization by image analysis of thin section highlighted an abrupt variation of porosity at the lower limit of the tilled layer in CT (Fig. S1). The ANOVA showed that management (M), depth (D), and their interaction, significantly affected total macroporosity (Table S2). In the CT plots, soil macroporosity in the surface layer (0.05-0.1 m) was much higher than in the underlying layer (0.1-0.2 m) and across the whole NC profile, where there was no significant depth-related variation. The difference was mainly due to a higher frequency of elongated pores (Table 2). Regular pores were influenced by management, with NC showing higher values than CT (Tables 2 and S2). As far as the pore size is concerned, the position (P) factor was not significant, whereas there were significant MxDxP and MxP interactions (Table S2) for transmission pores (50-500 μm) and fissures (>500 μm), respectively. The highest frequency of fissures was observed at both sampling positions in the CT surface layer, with inter-row showing a very high fissure percentage (22.48%, corresponding to 78% of total macroporosity), significantly exceeding that underneath the canopy (Table 2). The highest percentage of transmission pores, instead, was measured underneath the canopy in the surface layer of CT.

The bulk density was significantly affected by D and MxD interaction (Table S2). The deeper layer of CT showed the highest BD value, which was significantly larger than under NC and with a significant increase respect to the soil surface. Consistently with the total macroporosity values, the lowest BD was detected at 0-10 cm depth in CT; however, there was no significant difference from the NC surface layer (Fig. 2).

Tillage significantly reduced MWD_{dry} (6.6 mm) compared to NC (11.5 mm), whereas MWD_{dry} was not affected by the distance from the plant. The 4.75-10 mm and >10 mm aggregate size classes resulting from dry-sieving were the most abundant in terms of mean percentage frequency distribution (18.6 and 47.0, respectively). However, we chose the former for wet-sieving analysis, due to the high standard deviation and coefficient of variation of the latter (*st_dev* 24.46 and *cv* 52.06).

The MWD_{wet} was significantly influenced by management, position and their interaction (Table S2). Regardless of distance from the plant, NC always showed a very high MWD_{wet} if compared to the theoretical maximum of 7.375 mm for the 4.75-10 mm size class aggregates. Under CT, the MWD_{wet} values were significantly lower than under NC, especially in the inter-row space, where a drastic decrease occurred (Fig. 2).

The AC was significantly affected by MxD interaction, while AWC was influenced mainly by management (Table S2). NC increased AWC in the 0-10 cm layer compared to CT. The latter, instead, induced a temporary increase of AC, but in the top layer only. In the CT deeper layer AC reached the lowest value (Fig. 2).

3.3. Concentration and storage of organic carbon pools

Soil management induced a different organic C distribution pattern, with NC leading to a relatively uniform concentration of the organic C pools between underneath the canopy and inter-row, and CT to a higher concentration of TOC, TEC and HC underneath the canopy compared to inter-row (by 25%, 70% and 85% at 0-10 cm depth, and by 17%, 71% and 60% at 10-20 cm depth, respectively) (Fig. 3 and Table S3).

In the upper 10 cm layer, NC compared to CT achieved 20% more TOC and 41% more HC underneath the canopy, and 40% more TOC and 107% more HC in inter-row. The TEC fraction, instead, differed between treatments only in the inter-row, with a 75% higher concentration in NC plots. In the bottom soil layer, both TEC and TOC concentration were higher in CT than in NC when measured underneath the canopy (by 22% and 78%, respectively). The HC fraction was similar under the two treatments, regardless of the sampling position.

When considering the organic C stored in an equivalent soil mass down to 20 cm depth (Fig. 4 and Table S3), none of the fractions varied with management underneath the canopy; on the other hand, all organic C pools were greater in the inter-row space under NC (+21% TOC, +50% TEC and +63% HC). The spatial distribution of TOC stock between the two sampling positions within each management was similar to that of TOC concentration (Fig. 4). No significant differences in the degree of humification (DH) were found at any depth or sampling position between NC and CT, neither in concentration nor in stock terms.

Regarding water-stable aggregate size distribution, almost 90% of stable aggregates belonged to the 4.75-10 mm size class in NC without any difference between the canopy and the inter-row area. On the contrary, significant differences were detected between the sampling positions in CT. In fact, the soil underneath the canopy had the highest percentage of water-stable aggregates in the larger size class (4.75-10 mm), while the soil from inter-row in the smaller one (0.05-0.25 mm) (Fig. 5A and Table S4).

The average TOC content in the aggregate-size fractions was 10.7 g kg^{-1}. When expressing TOC concentration in soil aggregates in terms of g C per kg of aggregate fraction, the 10-4.75 mm size class showed a greater TOC concentration than the smaller ones. Within the 10-4.75 mm class, NC had a higher TOC than CT, but in the inter-row only, whereas no significant TOC differences between treatments or positions were found in the smaller size aggregate classes (Fig. 5B and Table S4).

When expressing TOC concentration in soil aggregates as g C per kg of soil, the differences in TOC content reflected the trend of aggregate frequency distribution, with TOC values ten times higher in the 10-4.75 mm class than in the lower size classes (Fig. 5C and Table S4). The differences in the aggregate TOC concentration between NC and CT were significant in the largest aggregate size class, with higher values in NC than in CT at both distances from the tree, and in the aggregates of the smallest size class, with a higher TOC content under CT. The distance from the plant had a significant effect on the 10-4.75 mm class only, with TOC being higher in the inter-row space than underneath the canopy in NC, and lower in CT.

3.4. Soil microarthropods community and biodiversity

More than 13,500 microarthropod individuals belonging to 19 BFs were collected from 24 soil samples. The following groups were common to all samples: Acari (53.7%), Collembola (35.9%), Pauropoda (2.6%), Hymenoptera (2.3%), Diplura (1.5%), Diptera larvae (1.1%) and Symphyla (0.4%). Other microarthropod groups, including Heteroptera, Diplopoda, Isopoda, Araneida, Chilopoda, Coleoptera (adults and larvae), Psocoptera, Thysanoptera, Pseudoscorpionida, Embioptera, were sporadically present (< 40 specimens/BF). Overall, the group of Acari was dominated by Oribatida, which accounted for 51.3% of all mites, followed by Prostigmata (26%), Mesostigmata (20.7%) and Astigmata, occurring only in CT (2.1%).

The composition of microarthropod community according to the feeding habits is reported in Table 3. Despite differences in soil condition and management, most of the trophic groups were widespread at all sampling points: polyphagous, predatory and micro-saprophagous were the most common groups; micro-saprophagous and predatory Acari were abundant under the plant canopy in CT, while phytophagous groups in NC. In the inter-row under CT, the abundance and variability of feeding habit of microarthropods were reduced (i.e., the mycophagous were all astigmatid Acari *Tyrophagus* sp.).

The analysis of abundance of the three main groups showed that the MxP interaction was significant for Acari only (Fig. 6, Table S5). Tillage negatively affected the density of "Other arthropods" and, to a lesser extent, that of Collembola. A higher density of Acari was measured underneath the canopy, whereas no difference between the sampling positions were found for the other groups. Concerning microarthropod biodiversity, the Shannon index was sensitive to differences between the management systems and evidenced the highest biodiversity in NC plots; the canopy cover affected the microarthropod eco-morphological diversity (BF richness), the Margalef and BSQar indices more than tillage (Table 4). Focusing on the BSQar index, the inter-row under CT showed a halved mean value due to the absence of the eudaphic forms.

3.5. Relationships between soil properties

Only the first two components resulting from the PCA (Table 5), accounting for about 71% of total variance, showed significant relationships between soil physical, chemical and biological parameters. Overall, these components helped us understand the soil behavior under the two different management systems. In particular, the first component highlighted the relationships under NC, regardless of the distance from the tree, while the second component highlighted the relationships underneath the canopy under CT.

In the first component, the variables with excellent significance were soil biological and physical properties, namely the abundance of "Other arthropods" and, to a lesser extent, that of Collembola, which were inversely related to air capacity and total macroporosity, and positively related to aggregate stability (MWD_{wet}) available water content (AWC), regular_macropores and, to a lesser degree, to chemical variables, specifically humic and total organic carbon. In the second component, the variables with the highest loadings were physical and chemical: bulk density, which provides an overall measure of total soil porosity (micro- and macro-), was negatively related to the amount of total, humic carbon, and, to a lesser extent, to the abundance of Acari. In the third component, the abundance of Acari and Collembola were the only significant variables, which correlated positively to each other and to the niche differentiation.

4. Discussion

Sustainability of specific soil management practices can only be assessed using a comprehensive approach to quantify their impact on soil agro-ecosystem functions. Depending on the local soil properties, the management effect may range from ameliorative to destructive (Vogel et al., 2018). Under our experimental conditions it was clear-cut that soil conservation tillage and grass cover behaved differently.

Changes in yield and yield efficiency between years can be explained by alternate bearing, irrigation volumes and changes in climatic factors that took place during the three growing seasons. In the previous four years, NC plots produced less than tilled ones because of a too early establishment of the cover crop that had decreased tree size (Gucci et al., 2012). Since 2008, when trees occupied the full volume of space and soil, the yield and yield efficiency of both soil management treatments became more similar, as also reported by Gómez et al. (1999).

Unlike productivity, different soil management treatments, albeit both conservative, had marked effects on soil physical, chemical and biological characteristics. Under CT management the soil structure was strongly affected by the tillage carried out one month before the sampling date, as shown by the discontinuity observed at 10 cm depth. The upper soil layer under CT, with a high percentage of pores and an optimal BD value for a sandy loam soil, contrasted with results in the deeper layer, which exhibited BD values greater than 1.63 g cm^{-3} and AC of 0.084 m^3 m^{-3}. Such BD values may adversely affect root growth (USDA ARS/NRCS, 2001). Usually, AC values greater than 0.10 m^3 m^{-3} are recommended in order to prevent the occurrence of crop-damage or yield-reducing aeration deficits in the root zone (White, 2006; Reynolds et al., 2009).

The macroporosity increase in the surface layer of CT was qualitatively different in relation to the distance from the plant. Underneath the canopy it was associated with a greater proportion of transmission pores (50-500 μm), which play an important role in soil-water-plant relationships and, in general, in maintaining good soil structure conditions (Greenland and Pereira, 1977). On the other hand, in the inter-row space the porosity increase was mainly due to a higher percentage of pores greater than 500 μm (78% of total macroporosity), whose abundance usually reflects a worsening of soil structure functionality (Greenland and Pereira, 1977). Soil organic carbon amount and its distribution pattern across the orchard are key factors in determining those differences. It is widely accepted that organic matter compounds significantly contribute to the formation and stabilization of soil transmission pores, thus their larger accumulation underneath the canopy than in the inter-row under CT appears to be consistent with this explanation (Pagliai and Vignozzi, 2002). As for the amount of regular macropores, their higher occurrence under NC than under CT could be related to a higher biological activity (Pagliai and Vignozzi, 2002), enhanced by larger TOC availability supplied by the grass roots. Besides arthropods, such biological activity includes that of native arbuscular mycorrhizal fungi (Turrini et al., 2017).

Aggregate stability is one of the most important factors in soil conservation and maintenance of soil environmental functions. Its increase under NC reduced the risk of surface crusting, which conversely was very high under CT, especially in inter-row. This result confirms what previously reported by Gucci et al. (2012), who also observed a drastic reduction of soil water infiltration associated with increased surface crusting. A crucial property for the evaluation of soil ecosystem services is AWC. Based on AWC values, NC (AWC > 0.15 m^3 m^{-3}) can be classified as “good”, while CT (AWC ≤ 0.15 m^3 m^{-3}) as “limited” (Reynolds et al., 2009). The values of these functional properties could explain why olive trees did not show water deficit symptoms under grass cover (Gucci et al., 2012) and yields under both the soil management treatments were similar.

TOC stratification under NC was higher than under CT, due to greater organic matter input and overall less soil disturbance, which allowed larger organic matter accumulation near the soil surface. The lack of differences in the degree of humification (DH) would indicate similar effectiveness of the two management systems in terms of organic matter quality, even with different amounts of organic material and soil physical disturbance.

In terms of stock to 20 cm depth, organic C was not affected by soil management within the canopy area. Conversely, all organic C pools were increased by NC in the inter-row, confirming the higher C sequestration potential of soil under grass cover compared to tillage, due to both the greater input of organic residues and higher physical protection of soil organic matter inside more stable aggregates.

Aggregates disruption as a consequence of tillage (Six et al., 1999) occurred completely up to the smallest size fractions, and the different distribution pattern was evident in the 10-4.75 mm size class. An involvement of organic matter in soil aggregate stabilization was evident only in the 10-4.75 mm aggregates of NC compared to CT in the inter-row area, where grass cover may have enriched the soil with more labile organic C forms deriving from the fine root systems which, in turn, may have favored the formation of large aggregates. On the other hand, the inter-row space under CT had a larger proportion of < 0.25 mm aggregates, which exhibited an overall higher amount of organic C when this was expressed in relation to the whole soil (g C kg soil^{-1}). However, this increase could have important implications on C sequestration in the longer term. In fact, it has been hypothesized that slaking-resistant small aggregates could be preferential sites for long-term organic matter preservation in soils by physical entrapment, which contributes to organic C stabilization by interaction with mineral surfaces (Virto et al., 2010).

Decomposition of soil organic matter by microarthropods and other organisms is crucial to the functioning of soil ecosystem because of its substantial role in ecosystem services, and in particular in plant growth and primary productivity

A number of environmental factors, such as climate, distance from the plant, management practices (particularly soil tillage) affected the assemblage and activity of soil microarthropods at the microscale, thus interfering with their role in the transformation of organic residues and nutrient cycle. In the study case the effect of tillage, carried out one month before the sampling, and the lack of rainfalls mainly affected soil structure characteristics, causing a reduction of soil microhabitat diversity and, as a consequence, of microarthropods biodiversity (cit).The microarthropod community confirmed to be very sensitive to soil management, as also reported in other studies with different crops, land uses (Mazzoncini et al., 2010; Gagnarli et al., 2015) and tillage practices (Rodriguez et al., 2006). In this specific case, the effect of tillage was maximum on ‘Other arthropods’ and Collembola groups, whereas Acari showed a higher resistance to soil disturbance (Nannelli and Simoni, 2002). In this regard, it is known that the structure and diversity of oribatids are studied to assess management or land use changes (Zaitsev et al. 2006) and differ from those of other microarthropods by less sensitiviness to soil perturbation due to their robust cuticola (Simoni et al. 2018).

As far as the ‘Other arthropods’ group is concerned, Formicidae, Protura and Araneida, regardless of their feeding strategy, were completely absent in the inter-row space under CT, whereas Symphyla, Diplura, Pauropoda and Isopoda were much less abundant compared to NC, showing high sensitivity to stress in soil habitat. Soil microarthropods are often spatially aggregated, following the distribution of food resources such as plant roots and organic debris (Griffiths, 1994); in our experiment they may have been favoured by the larger food resources provided by the above- and below-ground plant biomass scross the inter-row of NC, as well as in the canopy areas, where the they may have also benefited from higher protection against solar irradiation (van Eekeren et al., 2007; Zhang et al., 2016). In particular, the olive canopy seems to create good microenvironmental conditions for predators, generalist Acari and Collembola, reflecting the existence of patches of organic matter that lead to eruption of many r-strategists (Behan-Pelletier, 2003).

The high BF richness indicated a strong niche differentiation within the olive orchard. The abundance of eudaphic forms was reflected in high BSQ_{ar} index values, similar to the ones recorded in permanent grassland and wood (Menta, 2012), but also in abandoned and productive olive orchards of Southern Italy

(Gagnarli, pers. comm.). Menta et al. (2017) suggested a BSQ_{ar} value of 93.7 as a threshold to discriminate between poor and good quality soils.

The PCA confirmed, as a whole, the role of the organic matter in ensuring good soil structural conditions, as well as the involvement of the humified organic fraction in soil structure stabilization and improvement of soil water retention capacity. The relationship between soil physico-chemical parameters and microarthropod community is still poorly understood. The PCA interpretation provided information about the habitat in which the three groups of micro-arthropods found the most suitable conditions for their development. Moreover, considering microarthropod abundance and their well-known role in soil formation and transformation (Culliney, 2013; Menta, 2012), we can hypothesize their involvement in the processes of soil structure stabilization and organic substance accumulation and transformation. According to the component 1, describing NC soil conditions, the "Other arthropods" and Collembola increased with increasing regular pores, which are recognized to be related to the soil biological activity (Pagliai and Vignozzi, 2002), AWC, MWD_{wet} and, to a lesser extent, HC and TOC. A high aeration (> macroporosity and AC), instead, would lead to a decrease of these groups of microarthropods, probably due to a drier microenvironment. The major role of soil biota in aggregate formation and stabilization is generally acknowledged (Oades, 1993), but direct empirical evidence for microarthropods is scarce (Maaß et al., 2015). In particular, there are only a few studies that investigated the interaction mechanisms between soil structure and Collembola (Siddiky et al., 2012a, b; Maaß et al., 2015). In the component 2, describing soil conditions underneath the canopy under CT, Acari confirmed their relationship with soil organic matter and soil structure (Behan-Pelettier, 2003). Their number seemed to raise as soil organic matter increased and soil density (BD) decreased. Actually, soil compaction or poor food resources (Marshall, 2000) are limiting factors for Acari abundance; several studies have found that the latter increases with increasing soil pore volume (Vreeken-Bruijs et al., 1998; Ducarme et al., 2004). In this study the higher correlation of Acari with soil bulk density rather than macroporosity, could be explained keeping in mind that bulk density, being a function of both micro- and macro-porosity is more able to identify the best conditions, in terms of soil aeration and moisture, for the growth of micro-organisms that some Acari feed on. Microsaprophagous Acari, very abundant under the canopy in CT, would confirm this hypothesis. They are considered primary colonizators in disturbed or newly formed soil (Russell et al., 2010); in such conditions the plant effect is an important determinant of the soil food web complexity. It is perceptible the wide range of causal interactions between microarthropods, soil organic matter and the soil physical status, and further research is needed to comprehensively interpret them.

In conclusion, a sustainable soil management, able to combine production objectives with environmental protection goals, is one of the priorities of the 2014-2020 Common Agricultural Policy. In terms of carbon sequestration, biodiversity and water movement/retention, our results should encourage the adoption of natural grass cover as an alternative to conservation tillage for a better ecological sustainability of olive orchard management in the Mediterranean region.

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Table 1
Fruit and oil yield, expressed in terms of absolute yield and yield efficiency (fruit yield/TCSA[†] or oil yield/TCSA), under the two soil management systems. The values are means ± standard errors of four trees per treatment. Values with different lower case letters within each year are significantly different at P ≤ 0.05, Duncan test.

Year	Soil management[‡]	Irrigation	Fruit yield (g tree^{-1})	Fruit yield/TCSA (g dm^{-2})	Oil yield (g tree^{-1})	Oil yield/TCSA (g dm^{-2})	Fruit fresh weight (g)	Mesocarp oil content (% D.W.)
2011	NC	Rainfed	3559 ± 448	2145 ± 308	485 ± 64	296 ± 53	1.54 ± 0.01	58.4 ± 0.59
	CT	Rainfed	5296 ± 915	2257 ± 443	525 ± 108	227 ± 56	1.65 ± 0.11	62.2 ± 2.26
2012	NC	Deficit	23319 ± 2133	11339 ± 2058	3024 ± 340	1483 ± 315	2.69 ± 0.08	66.9 ± 0.99
	CT	Deficit	23629 ± 4469	10069 ± 2843	2983 ± 565	1268 ± 354	2.60 ± 0.09	67.0 ± 0.53
2013	NC	Deficit	16560 ± 2216	6785 ± 960	2086 ± 318	851 ± 127	2.92 ± 0.03 a	63.6 ± 1.13
	CT	Deficit	19030 ± 3690	6836 ± 1636	1772 ± 339	635 ± 150	2.31 ± 0.12 b	64.2 ± 0.50

[†] TCSA = trunk cross sectional area.
[‡] NC = natural grass cover, CT = conservation tillage.

Table 2
Soil macroporosity (> 50 µm), expressed as percentage of macropores belonging to different shape (regular, irregular and elongated) and size classes (50–500 µm, > 500 µm) and as total percentage of macropores. In the last column, the proportion of pores larger than 500 µm to the total macroporosity is reported. Means with different letters are significantly different at P ≤ 0.05, Duncan test.

Manage-ment[†]	Depth (cm)	Position[‡]	Shape			Size class (µm)		Total	> 500 (%)
			Regular	Irregular	Elongated	50–500	> 500		
NC	5–10	UC	1.53 ab	2.27	3.26 b	5.11 b	1.95 c	7.06 b	28
		IR	1.69 a	2.62	4.04 b	5.32 b	3.03 bc	8.35 b	36
	10–15	UC	1.31 abcd	2.27	4.79 b	4.41 b	3.96 bc	8.37 b	47
		IR	1.46 abc	2.01	3.10 b	5.20 b	1.37 c	6.57 b	21
CT	5–10	UC	1.02 bcd	2.84	21.98 a	16.04 a	9.80 b	25.84 a	38
		IR	0.85 d	2.67	25.38 a	6.42 b	22.48 a	28.90 a	78
	10–15	UC	1.00 cd	2.13	2.27 b	2.52 b	2.88 bc	5.40 b	53
		IR	1.36 abcd	2.69	3.43 b	4.62 b	2.86 bc	7.48 b	38

[†] NC = natural grass cover, CT = conservation tillage.
[‡] UC = underneath the canopy; IR = inter-row space.

Table 3

Classification[†] of soil microarthropod groups by main feeding guilds, under the different management systems (natural grass cover, NC; conservation tillage, CT) and sampling position (underneath the canopy, UC; inter-row space, IR).

			Macro-saprophagus	Micro-saprophagus	Mycophagus	Polyphagus	Predators	Phytophagus
NC	UC	Acari	+	+	+	+ +	+ + +	+
		Collembola		+	+	+ + +		+
		Other arthropods	+	+ +	+	+	+	+
	IR	Acari	+	+	+	+	+	
		Collembola		+ +	+ + +	+		+
		Other arthropods	+	+	+	+	+	
CT	UC	Acari	+	+ + +	+	+ +	+ + +	
		Collembola		+	+	+ + +		+
		Other arthropods	+	+	+	+	+	+
	IR	Acari	+	+	+ +	+	+ +	
		Collembola		+		+ +		+
		Other arthropods	+	+		+	+	+

[†] Number of specimens within each class: + n < 50; + + n = 50–99; + + + n > 100 for each MxP used for assessing rough estimates of the potential for maintaining ecosystem services such as biological regulators or pest control.

Table 4

BF[†] diversity indices of soil microarthropods and BSQ_{ar} index under the different management systems[‡] and at the different sampling position[§]. Means with the same letters within each column are not significantly different at $P \leq 0.05$, Tukey test.

		Richness (S)	Shannon (H)	Margalef (d)	BSQ_{ar} (mean)
NC	UC	18a	1.23a	2.02a	189.0a
	IR	15b	1.28a	1.71b	164.7b
CT	UC	17a	0.86c	1.92ab	185.7ab
	IR	8c	0.96b	0.98c	92.7c

[†] BF = Biological Formes.
[‡] NC = natural grass cover, CT = conservation tillage.
[§] UC = underneath the canopy; IR = inter-row space.

Table 5
Results of the PCA: eigenvalues of factors and factor loadings of the variables.

	Factor 1	Factor 2	Factor 3
Acari	−0.29	**0.52**	**0.73**
Collembola	**−0.59**	−0.07	**0.68**
Other arthropods	**−0.76**	0.02	0.39
TOC	**−0.49**	**0.82**	−0.18
HC	**−0.56**	**0.76**	−0.09
BD	−0.33	**−0.88**	0.14
MWD_{wet}	**−0.87**	0.25	−0.30
AWC	**−0.73**	0.05	−0.43
AC	**0.88**	0.36	−0.07
Reg_pores	**−0.81**	−0.40	0.00
Tot_pores	**0.80**	0.35	0.38
Eigenvalue	*5.0*	*2.8*	*1.6*
% of total variance	*45.5*	*25.3*	*14.9*
Cumulative % of total variance	*45.5*	*70.8*	*85.7*

In bold values higher than I0.45I.

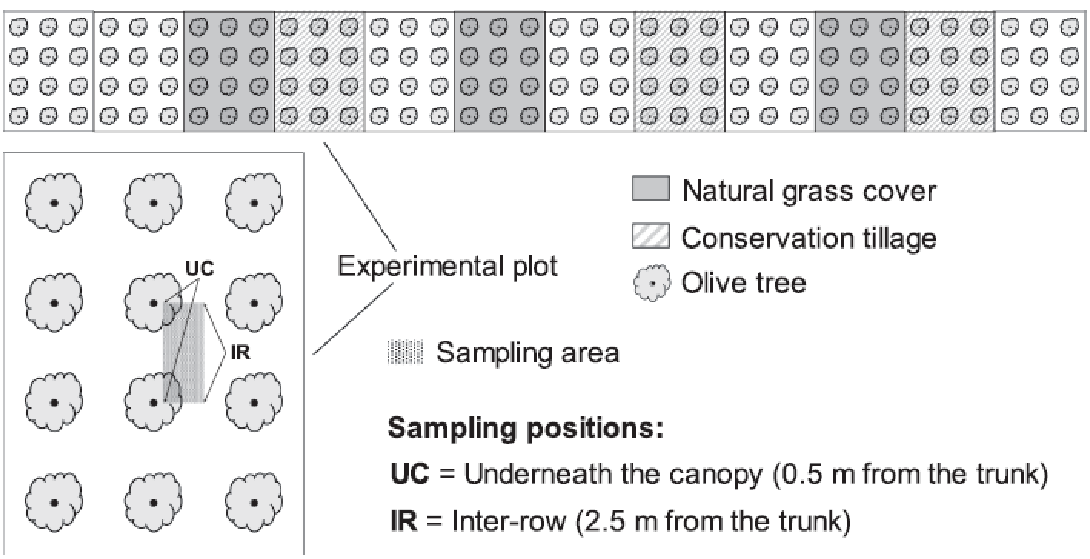

Fig. 1. Layout of the experimental design; distribution of treatments across the different plots and sampling positions.

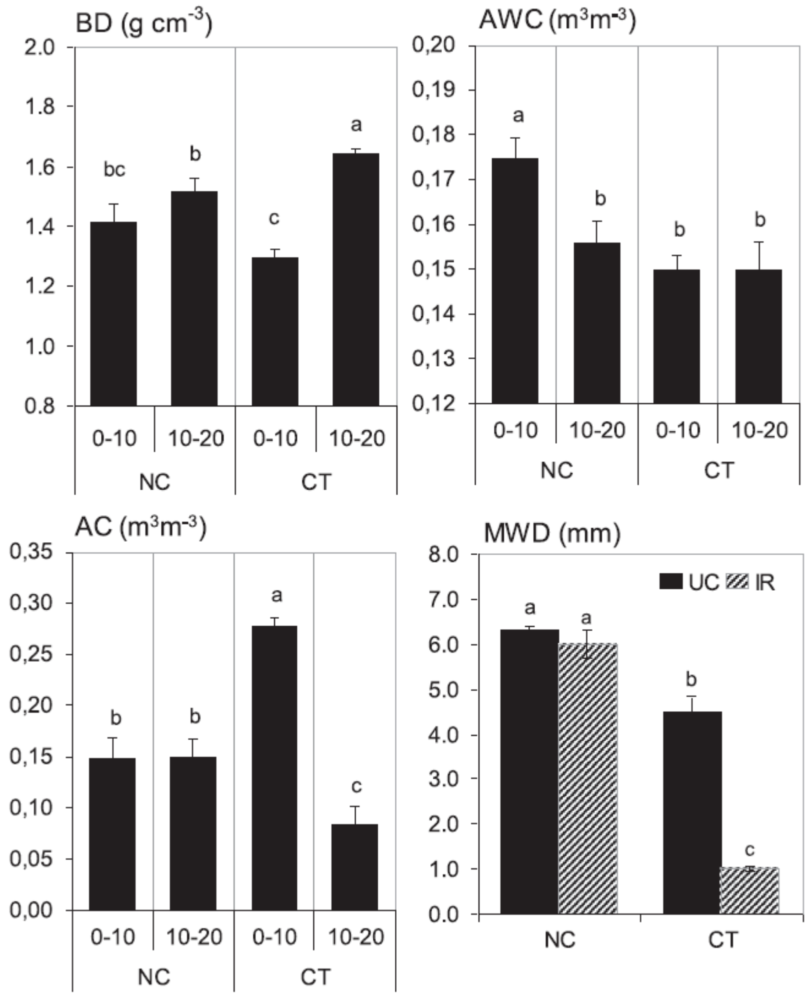

Fig. 2. Soil physical properties under the different management systems: bulk density (BD), air capacity (AC), available water capacity (AWC) and mean weight diameter (MWD). Values are means ± standard errors. Different letters indicate significant differences between soil management treatments and depths for BD, AC and AWC, between soil management treatments and position for MWD ($P < 0.05$), Duncan test.

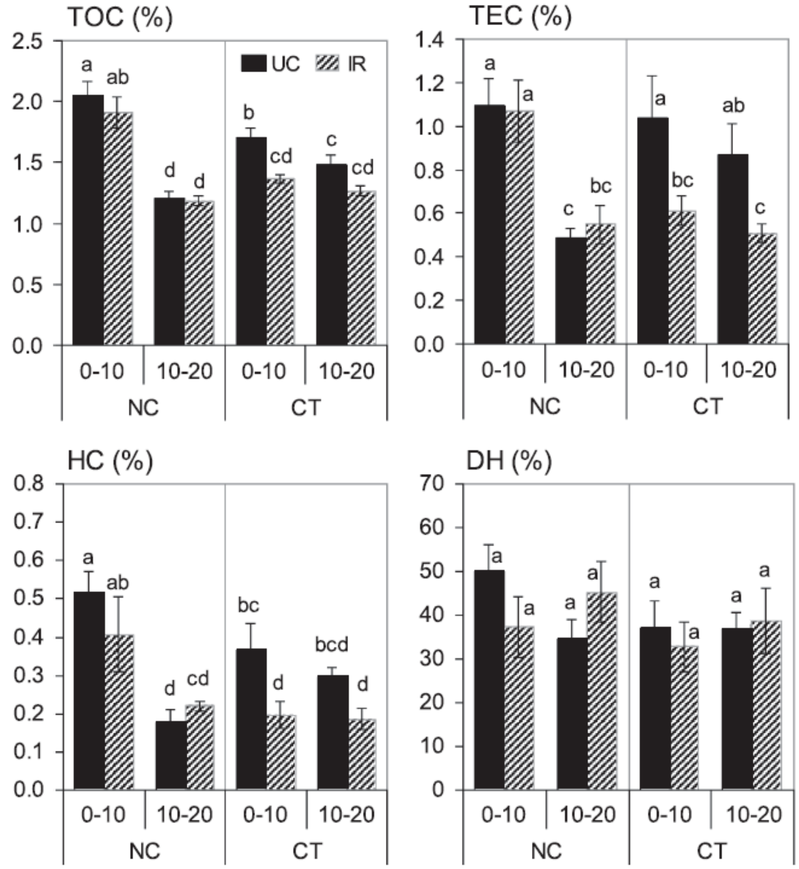

Fig. 3. Soil total (TOC), extractable (TEC) and humified (HC) organic carbon concentration and degree of humification (DH) at different depth increments under natural grass cover (NC) and conservation tillage (CT). UC = underneath the canopy; IR = inter-row. Values are means ± standard errors. Different letters indicate significant differences between soil management treatments, depth and position ($P < 0.05$), Duncan test.

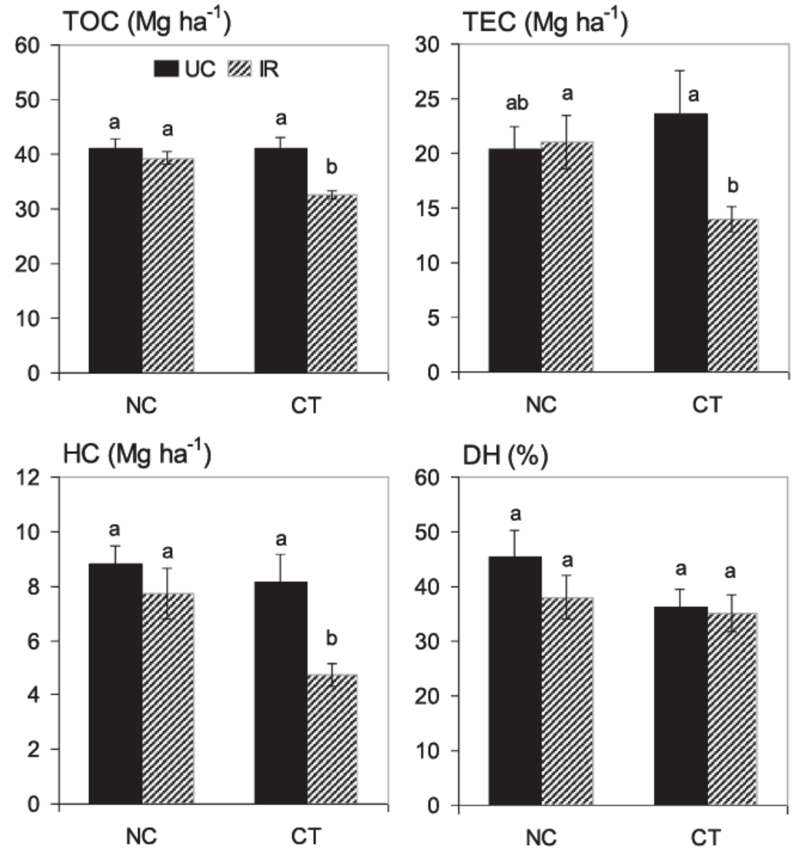

Fig. 4. Soil total (TOC), extractable (TEC) and humified (HC) organic carbon stocks and degree of humification (DH) in a cumulative equivalent mass of soil to 20 cm depth under natural grass cover (NC) and conservation tillage (CT) (equivalent soil mass = 2474 Mg ha^{-1}). UC = underneath the canopy; IR = inter-row. Values are means ± standard errors. Different letters indicate significant differences between soil management treatments and position ($P < 0.05$), Duncan test.

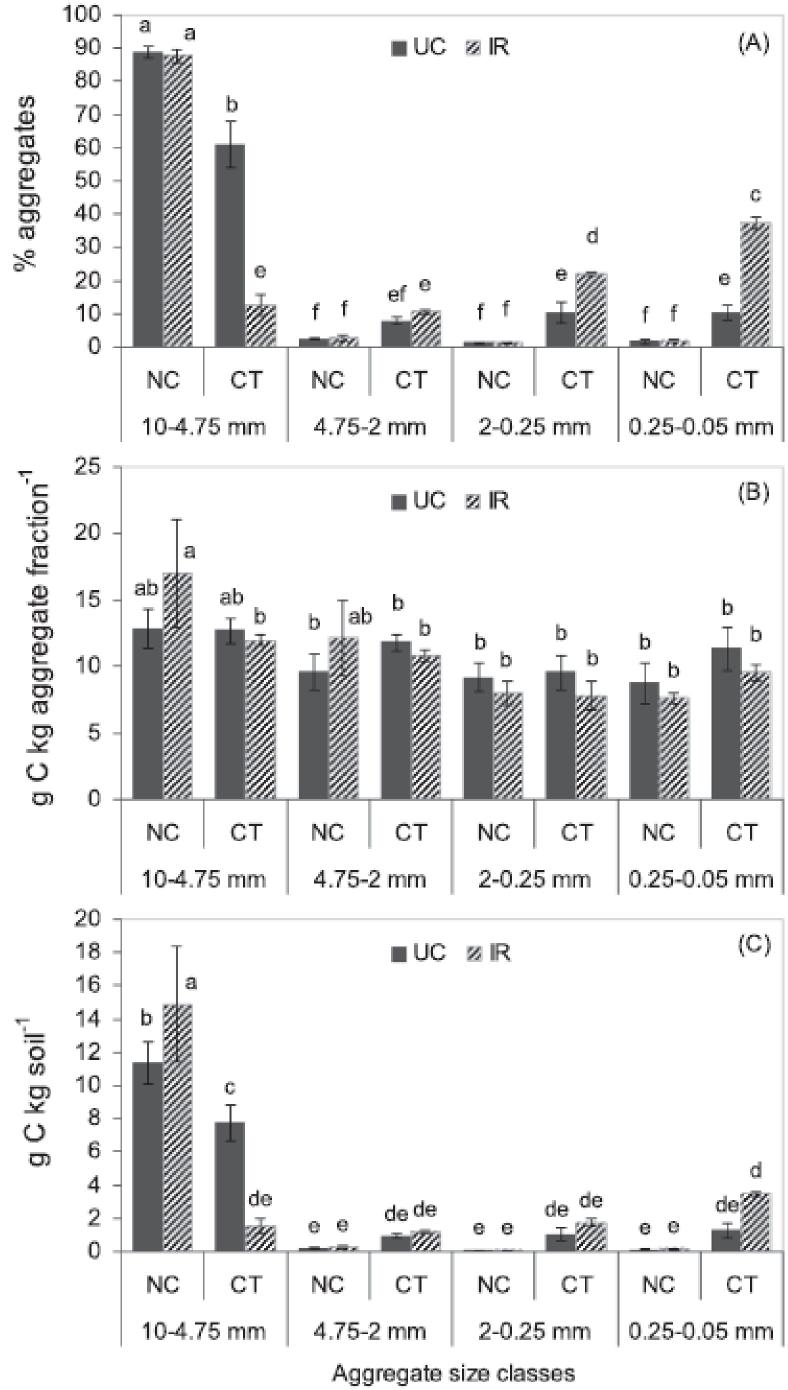

Fig. 5. Distribution of soil water stable aggregates among different size classes (A) and OC content within each class, expressed as g TOC/kg aggregate fraction (B) and as g TOC/kg soil (C). UC = underneath the canopy; IR = inter-row. Values are means ± standard errors. Different letters indicate significant differences between soil management treatments, aggregate size classes and position ($P < 0.05$), Duncan test.

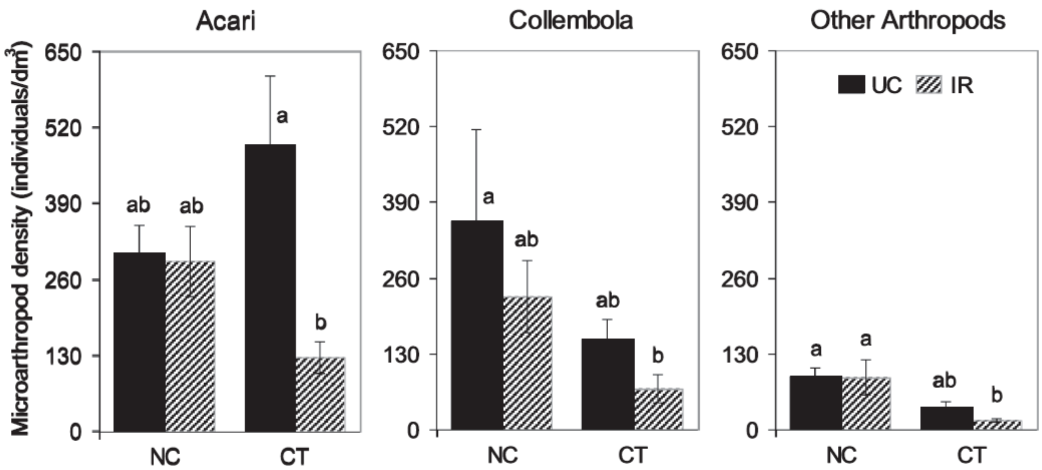

Fig. 6. Average abundance of Acari, Collembola and "Other arthropods" under natural grass cover (NC) and conservation tillage (CT), at two different distances from the plant (UC = underneath the canopy; IR = inter-row space). Values are means ± standard errors. Different letters indicate significant differences between soil management treatments and position ($P < 0.05$), Duncan test.